A LABORATORY COURSE IN PHYSICS

FOR SECONDARY SCHOOLS

BY

ROBERT ANDREWS MILLIKAN, Ph.D.
Assistant Professor in Physics at the University of Chicago

AND

HENRY GORDON GALE, Ph.D.
Instructor in Physics at the University of Chicago

GINN & COMPANY
BOSTON · NEW YORK · CHICAGO · LONDON

66.10

The Athenæum Press
GINN & COMPANY · PROPRIETORS · BOSTON · U.S.A.

INTRODUCTION

Although laboratory work is now generally recognized as an indispensable part of any adequate course in elementary physics, it is nevertheless a lamentable fact that there are still some schools in which it is not attempted at all, while there are others in which, despite the most expensive equipment, the laboratory fails, on the whole, either to interest or instruct.

Both of these conditions are probably attributable to one and the same cause. In our modern glorification of the laboratory method, particularly of exact, quantitative measurements, and in our haste to get away from the superficial, descriptive physics of thirty years ago, some of us have undoubtedly gone so far as to defeat our own aims. We have made the laboratory an impossibility in schools which are financially weak, because we have made its expense prohibitive; and we have made it a disappointment in other schools which are financially strong, because in our eagerness to show our students exactly *how much* we have neglected to show them *how* and *why*. In short, the gravest danger which threatens the efficiency of the high-school laboratory to-day is the danger which arises from the creeping over of the methods and the instruments of research and specialization from the university into the high school, where they have absolutely no place, — the danger that principles shall be lost sight of in the bewildering details of refined methods and refined instruments.

The primary aims of the authors in the development of this course have been: (1) to make it a continuous and inspiring laboratory study of physical phenomena, and as far as possible

removed from a mere drill in physical manipulation; and (2) to reduce apparatus to its simplest possible terms and yet to present a thorough course in laboratory physics.

Such success as has been attained in the accomplishment of these ends has been due not merely to a large amount of labor and experimentation on the part of the authors, but also to suggestions which have come in from the score of schools in which this course has been given a thorough trial during the past three years, and especially to the expert assistance of the instrument maker, Mr. William Gaertner, who has so simplified the design of the apparatus herewith presented that a large part of it can now be made at home if desired. Even if it is all purchased, it need not cost more than fifty dollars for a complete set, and six such sets have been used most satisfactorily at the University of Chicago in conducting laboratory sections of twenty pupils. The authors recommend, however, that wherever conditions will permit, all of the pupils of a section be kept working upon the same experiment at the same time. This arrangement requires about half as many sets as there are pupils. With instructions as complete as those here given, the experience of a number of schools has shown that with fifteen sets one instructor can successfully conduct a class of as many as thirty pupils. Great care has been taken to incorporate only such experiments as experience has shown to be workable with large classes and with a minimum tax upon the teacher's time outside of laboratory hours.

Another feature of the course is that the experiments do not presuppose either any previous study of the subject involved, or any antecedent knowledge of physics. The laboratory work may be kept in advance of the class-room discussion throughout the entire course if desired. Indeed, in their own elementary work the authors prefer to let more than half of the experiments constitute the student's first introduction to the subject treated. Furthermore, students are neither instructed nor advised to study

their experiments before entering the laboratory, for each experiment has been arranged to carry with it its own introduction.

As was to have been expected from the statement of the aims of the course, it has been made a thorough mixture of qualitative and quantitative work. Indeed, the endeavor to make an elementary laboratory course either wholly qualitative or wholly quantitative seems to the authors to result inevitably in artificial and irrational distinctions, and to be perhaps the most fruitful cause of the failure of laboratory work.

The most approved and most satisfactory division of time between the class room and the laboratory is three single periods per week in the former and two double periods in the latter. Abundant experience in schools quite variously situated has shown that the work herein outlined can be easily completed in two such eighty- or ninety-minute periods per week for thirty-six weeks, even when all the notebook work is done in class. The length of the experiments has not, however, been adjusted so as to fit, in all cases, one school period; first, because the lengths of school periods are so different in different schools, and second, because the authors have not wished to sacrifice the logical development of a subject to a consideration which is after all wholly artificial and mechanical. The division into experiments is made on the basis of subject-matter rather than of time. A considerable number of the experiments will be found to require two periods, while in a few instances two experiments can be performed in a single period. This arrangement has not been found to be at all objectionable where all of the pupils work simultaneously upon the same experiment, and even in courses which are conducted with but a few sets of apparatus the difficulties arising from this source have been found to be trifling.

In case individual teachers find it desirable to shorten or modify the course, the subdivisions of each experiment make

omissions easy and simple. It has been an especial aim of the authors to make both this course and the class-room text which it is designed to accompany sufficiently flexible to give full play to the individuality of the teacher. Both books have therefore been made complete enough to allow of a considerable range of choice. The two books together constitute a one-year course in high-school physics. The laboratory portion has, however, been made completely independent of the other portion, and in a number of instances has been given as a short course by itself with very satisfactory results. It is the firm conviction of the authors, based upon a considerable experience, that in schools in which only a short course in physics can be offered, a course of this sort with laboratory work for its backbone is much more satisfactory than one based upon an abridgment of a class-room text.

With respect to the notebook the authors can express but little sympathy with any rigid, mechanical form of arrangement to which all experiments must be forced to conform, and they are convinced that in some schools the real study of physics has been sacrificed to the study of notebook form. Their directions to their own pupils are, "Fill out your notebook as you proceed with your work in the laboratory, and let it be merely a brief running record of what you do, of what results you obtain, and of what conclusions you draw." Blank books of coördinate paper are required, and left-hand pages are used for scratch-book purposes, i.e. they contain preliminary observations and computations, while right-hand pages contain the orderly outline of the work, including the title and subheads of each experiment as found in the manual, a very brief statement of what is done under each, an orderly statement of results (copied in some instances from the left-hand page), and conclusions. Outline drawings are encouraged whenever the idea can be expressed more quickly and clearly in a drawing than in

words. In order to place especial insistence upon the conclusions, questions have been freely scattered through the text, the answers to which generally involve the conclusions which are to be drawn. In schools in which double laboratory periods cannot be obtained time may be gained, without sacrificing the real study of physics, by having the orderly part of the notebook work done at home. If still further time must be gained, the authors prefer to save it at the expense of the written work rather than at that of the experiments, oral answers and discussion in the laboratory replacing some of the written work called for.

For the benefit of those who use both this book and the authors' class-room text a suggested time schedule for a thirty-six weeks' school year is inserted in Appendix A. Whether this particular schedule is followed or not, it seems to the authors a matter of great importance that each teacher begin his year with some well-considered time schedule before him, and that he plan each lesson and make his omissions and additions with this schedule in mind. Otherwise it almost invariably happens that the subjects treated in the first half of the text receive a disproportionate amount of time.

In Appendix C will be found a complete list of the apparatus desirable for the course. The experiments do not, however, preclude the use of the more expensive forms of instruments which are already common in the equipment of high schools, although the authors believe the simpler apparatus to be, in general, the more instructive.

The form which has been given to the Boyle's Law experiment (page 26) was first called to the authors' attention by Mr. C. H. Perrine of the Wendell Phillips High School, Chicago, although a modification of the same method is found in the admirable laboratory manual by Nichols, Smith, and Turton. The experiment on the cooling of acetamide through its change

LABORATORY PHYSICS

EXPERIMENT 1

EXPERIMENTAL DETERMINATION OF π

(The ratio of the circumference of a circle to its diameter)

(*a*) *Measurement of circumference.* Measure the circumference to an accurately turned disk in the following way. Scratch a short mark A (Fig. 1) on the face of the disk perpendicular to its edge. Stand the disk on edge on a meter stick so that the mark A is very accurately above some chosen division B, e.g. the 10-cm. mark of the meter stick.

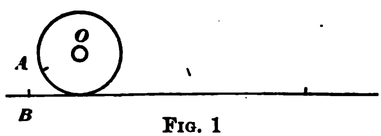


FIG. 1

Then, supporting the disk by causing the thumb and forefinger to meet through O, roll it very carefully along the meter stick until it has turned through one complete revolution. (Don't touch circumference in rolling.) The mark A will fall on some point of the scale. If it does not fall exactly on one of the millimeter divisions, in order to retain a decimal system throughout, record the fractional part of the last division in *tenths*, not in halves, thirds, or quarters.[1]

[1] Unfamiliarity with the metric system may make it seem more natural to estimate in halves, thirds, or quarters, but it will be easy to express the result in tenths if one reflects that .4 is a little less, and .6 a little more, than 1/2; .2 a little less and .3 a little more than 1/4; .1 a little less than .2, i.e. 1/5, etc.

Repeat the measurement and estimation four times, starting at a different point on the scale each time. Take a mean of these five readings as the most correct value of the circumference obtainable by this method.

Since the separate observations were uncertain in the tenths millimeter place, the mean will surely be uncertain in the hundredths millimeter place. To reserve places beyond this, then, would not only be useless but misleading, since it would indicate that the measurement was made to a higher degree of accuracy than it really was. The best usage in recording physical observations is to record one uncertain figure, but never more, except in recording the mean of a considerable number of observations, when one more figure may be retained, especially if the difference between the individual observations is slight. If this uncertain figure happens to be zero, it should be recorded like any other digit.

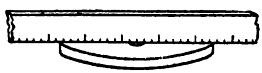


FIG. 2

(*b*) *Measurement of diameter.* Next measure the diameter of the ring with a meter stick held on edge as in Fig. 2. Record five observations taken along different diameters, and take the mean, estimating in each case to tenths of a millimeter.

(*c*) *Computation.* From these measurements compute π, the ratio of the circumference of a circle to its diameter. In the result save only one uncertain figure.

To find the first uncertain figure in the result, divide as in the illustration, underlining the uncertain figures throughout.

$$\begin{array}{r|r|l} 8.43\underline{6} & 26.5\underline{2} & 3.14\underline{3} \\ & \underline{25\ 30\underline{8}} & \\ & \underline{1\ 21\underline{20}} & \\ & \underline{843\underline{6}} & \\ & 368\underline{40} & \\ & \underline{3374\underline{4}} & \\ & \underline{\underline{30960}} & \end{array}$$

Compare the result of your measurement with that given by mathematical theory, viz. 3.1416. Find first the amount of the error, and then compute what per cent the error is of the whole quantity, e.g. if

the result of your measurement is 3.143, then by taking the difference between this and 3.1416 we get

$$\begin{array}{l} 3.143 \\ \underline{3.1416} \\ \;\;.0014 = \text{error} \end{array} \qquad \begin{array}{l} 1\% \text{ of } 3.1416 = .031416 \\ \therefore \text{ Per cent of error} = \dfrac{.0014}{.031} = .045 \end{array}$$

In the last division only two significant figures were used in the denominator, since it is never necessary to find the per cent of error to more than this degree of accuracy.

Record measurements and computations as below:

Trial	*Diameter*	*Circumference*	
1	8.43	26.50	
2	8.45	26.55	
3	8.44	26.52	$\dfrac{\text{Circumference}}{\text{Diameter}} = 3.143$
4	8.43	26.50	
5	8.43	26.52	Error = .0014
	Mean 8.436	26.518	Per cent of error = .045

State in the notebook, beneath the results tabulated as above, what per cent of error would have been introduced into the result if you had made an error of .1 mm. in measuring the diameter. (Find what per cent .1 mm. is of the whole diameter 8.436.)

State, therefore, whether your error is more or less than should have been expected from reasonably careful measurements. (Put your answers into the form of complete sentences.)

EXPERIMENT 2

DETERMINATION OF THE VOLUME OF A CYLINDER

I. By computation from linear measurement.

(*a*) *Measurements.* Measure with a metric rule the inside depth of the cylindrical vessel shown in Fig. 8, in three different places, estimating as before very carefully to tenths of a millimeter.

Measure the inside diameter D with a vernier caliper,[1] if this instrument is available; if not, use the method of the previous experiment, taking pains that the edge of the meter stick is held in every case exactly across a diameter.

(*b*) *Computation.* Compute the volume of the cylinder from the area of the base $\left(\frac{\pi D^2}{4}, \text{ or } \pi R^2, R \text{ being the radius}\right)$ and the height L. Underline all uncertain figures, and save only two uncertain figures in the result.

The following illustrates the method of computation:

$$
\begin{array}{r}
R = 2.5\underline{13} \text{ cm.} \\
\underline{2.5\underline{13}} \\
\underline{7}\ \underline{539} \\
\underline{25}\ \underline{13} \\
1\ 25\underline{6}\ \underline{5} \\
5\ 02\underline{6} \\
\hline
R^2 = 6.3\underline{15}
\end{array}
\qquad
\begin{array}{r}
R^2 = 6.3\underline{15} \\
\pi = 3.14\underline{2} \\
\hline
\underline{12}\ \underline{630} \\
252\ \underline{50} \\
63\underline{1}\ \underline{5} \\
18\ 9\underline{45} \\
\hline
\pi R^2 = 19.8\underline{41}
\end{array}
\qquad
\begin{array}{r}
\pi R^2 = 19.8\underline{4} \\
L = 8.0\underline{1} \\
\hline
\underline{19}\ \underline{84} \\
158\ 7\underline{2} \\
\hline
158.\underline{91}
\end{array}
\quad
\begin{array}{l}
\\ \\ \\ \\
= \text{volume} \\
\text{in cubic} \\
\text{centimeters}
\end{array}
$$

[1] The vernier is a device for measuring fractional parts of a scale division. It consists of a movable scale AB arranged to slide along a fixed scale CD (Fig. 3). The object to be measured is placed between the jaws EF, which are so made that when they are in contact the zero of the sliding scale is opposite the zero of the fixed scale.

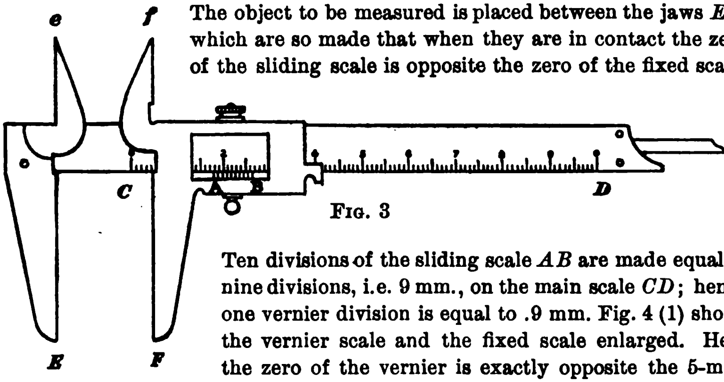


FIG. 3

Ten divisions of the sliding scale AB are made equal to nine divisions, i.e. 9 mm., on the main scale CD; hence one vernier division is equal to .9 mm. Fig. 4 (1) shows the vernier scale and the fixed scale enlarged. Here the zero of the vernier is exactly opposite the 5-mm. mark of the fixed scale, this being the relative position of the two scales when an object 5 mm. in diameter is placed between the jaws. Since one division on

Tabulate your results in some form similar to the following:

	First observation	*Second observation*	*Third observation*	*Mean*
Height of cylinder	= 8.26 cm.	8.25 cm.	8.25 cm.	$8.25\underline{3}$ cm.
Inner diameter of cylinder	= 6.04 cm.	6.03 cm.	6.04 cm.	$6.0\underline{37}$ cm.
	$\therefore R = 3.0\underline{19}$		$\therefore$ Volume =	$23\underline{6.2}$ cc.

Write in your notebook answers to the following questions, using complete sentences as in Experiment 1.

If the diameter of a circle is measured as 10.1 cm. when it is actually 10 cm., by what per cent will the square of the diameter as measured differ from the square of the true diameter? (If in doubt, work it out.) Hence what per cent of error will be introduced into the computed value of the area of a circle, if there is an error of 0.3 per cent in the measurement of the diameter?

AB is equal to only .9 mm., while one division on *CD* is equal to a whole millimeter, it follows that the mark 1 of the sliding scale *AB* is .1 mm. behind the mark 6 of the fixed scale; 2 on *AB* is .2 mm. behind 7 on *CD*; 3 is .3 mm. behind 8; 7 is .7 mm. behind 12, etc. Therefore, if the sliding scale were moved up so as to bring its mark 1 opposite the mark 6 on the fixed scale, its zero mark would move up .1 mm. beyond 5. If the vernier had moved up until its 5 mark were opposite 10 on *CD*, the zero mark would have moved .5 mm. beyond 5, etc. In general, then, it is only necessary to observe which mark on the sliding scale

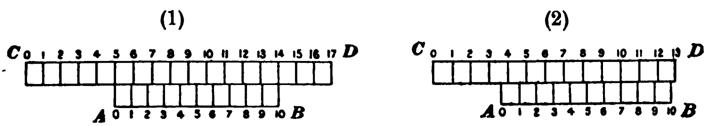


FIG. 4

AB is directly opposite a mark on *CD*, in order to know how many tenths of a millimeter the zero mark of *AB* has moved beyond the last division passed on *CD*. Thus the reading in Fig. 4 (2) is 3.7 mm. (.37 cm.), since the zero mark of the vernier has passed the 3-mm. mark on the fixed scale *CD*, and the 7 mark on the vernier is directly opposite some mark of *CD*.

In order that the *interior* as well as *exterior* dimensions of hollow objects may be readily determined, the jaws *ef* (Fig. 3) are added in many vernier calipers. These jaws are inserted just inside the walls and the reading taken as described.

If you misread the diameter of your cylinder by 0.1 mm., what per cent of error did you thus introduce into the diameter? into the computed area of the base of the cylinder? into the computed volume of the cylinder?

II. By weighing the cylinder first when empty and then when filled with water.

(*a*) *Weighing cylinder by method of substitution.* Place the empty cylinder with its ground-glass cover on the pan *B* (Fig. 5) of the balance, and add to the other pan any convenient objects, such as pieces of iron, shot, and bits of paper, until the pointer stands opposite the middle mark at *s*, the rider *R* being at zero.

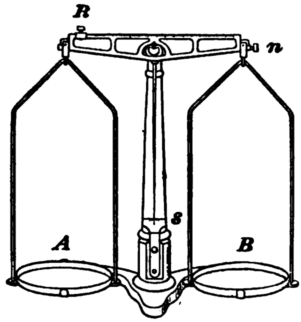


FIG. 5

Then replace the cylinder and cover by weights from the set in the following way. Find by trial the largest weight which is not too large, and place it on pan *B*. Add the equal weight, or, if there is no equal, the next smaller one, if it is not too heavy; add again the equal or next smaller weight, and so on, always working down from weights which are too large. This saves the delay and annoyance caused by adding a large number of small weights and at last finding that their sum is still too small.

When a balance has been obtained to within 10 g., slide the rider *R* along the graduated beam until the pointer stands opposite the middle mark at *s*. The weight of the body is then the sum of the weights on the pan plus the reading of the left edge of the index *R* on the graduated beam. Since each division of the scale on the beam represents one tenth of a gram, by estimating to fractional parts of a division we can obtain the weight by this method to hundredths of a gram.

The preceding is the rigorously correct method of making a weighing. It is called the *method of substitution.*

(*b*) *Weighing cylinder by usual method.* Next weigh the same object by the following simpler and quicker method. Empty the pans, move R to its zero point, and bring the pointer to the middle mark by altering if necessary the nut n (Fig. 5). Then place the object on pan A and find what weights must be added to pan B in order to bring the pointer to the middle mark again, the adjustment for weights smaller than 10 g. being made as above with the rider. Unless the difference in the two weighings is larger than one or two tenths of a gram, you may henceforth use the second method for all ordinary weighings; for the imperfections in inexpensive commercial weights, such as we are using, are likely to amount to as much as a tenth of a gram. Hence we are taking needless pains and adding nothing to the accuracy of the result by using the rigorous method.[1]

(*c*) *Weighing cylinder full of water.* Next fill the cylinder with water and place the cover over it, taking care that no air bubbles are left inside. Carefully wipe all moisture from the outside and weigh.

Refill the cylinder and repeat this last weighing in order to see how closely two observations can be made to agree. From the mean of these two weighings and the mean of the weighings of the empty cylinder and cover find the weight of the water.

Since 1 cc. of water weighs 1 g., the volume of the cylinder in centimeters is equal to the weight in grams of the water which it contains.

[1] The new method would be as correct as the method of substitution, provided we could know that the two balance arms are of exactly the same length (see *Principle of Moments*, p. 44). If, therefore, you get different results by this method and the method of substitution, you may know that the instrument maker did not succeed in getting the balance arms quite equal in length. Errors due to this cause are, however, usually very slight.

Tabulate results as follows:

	First weighing	*Second weighing*	*Mean*
Weight of empty cylinder and cover	= 221.6 g.	221.7 g.	221.65 g.
Weight of cylinder plus water	= 456.8 g.	456.6 g.	456.7 g.
∴ Weight of water alone	= 235.0 g.	∴ Volume =	235.0 cc.
Difference between volume by I and II	= 236.2 − 235.0 = 1.2 g.		
Per cent of difference	= (1.2 ÷ 235) × 100 = .51		

What per cent of error would an error of .2 g. in the weighing of the cylinder full of water introduce into your last measurement of the volume?

Do your results in I and II agree as well as they should in view of the probable errors which you have estimated are inherent in your two measurements of the volume?

Decide from your results which method of finding the volume is probably the more accurate.

EXPERIMENT 3

DETERMINATION OF THE DENSITY OF STEEL SPHERES

I. From weights and diameters of spheres.

(*a*) *Diameters of spheres.* Measure the diameters of several steel spheres with the micrometer caliper,[1] if this instrument is available. If not, the diameters may be obtained by placing the balls between two blocks, as indicated in Fig. 6, and measuring the distance between the blocks. If this method is used, however, it will be better to place

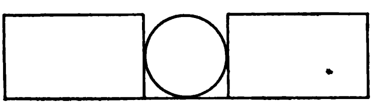


FIG. 6

[1] In the micrometer caliper (Fig. 7) the divisions upon the scale *c* correspond to the distance between the threads of the screw *s*. This distance is usually a half millimeter. Hence turning the milled head *h* through one complete revolution changes the distance between the jaws *ab* by exactly one half millimeter,

six or eight balls in a row between two meter sticks, set the blocks at the ends of the row, and divide the distance between the blocks by the number of balls. It will be best to use balls about 2 cm. in diameter. Take the mean of at least five diameter measurements.

Compute the volume of a sphere from the relation $V = \frac{1}{6}\pi D^3$, where V represents the volume and D the diameter. Here, and henceforth, instead of underscoring all uncertain figures as heretofore, you may simply retain in any product or quotient the same number of significant figures as there are figures in the least accurate factor which enters into the product or quotient.

and turning h through one fiftieth of a revolution changes the distance between ab by $\frac{1}{50} \times \frac{1}{2} = .01$ mm. If, then, there are fifty divisions upon the circumference of d, each division represents a motion of .01 mm. at b.

To make a measurement, turn up the milled head h (Fig. 7) until the jaws ab are in contact, i.e. until the milled head, held with light pressure between the thumb and finger, will slip between the fingers instead of rotating further.

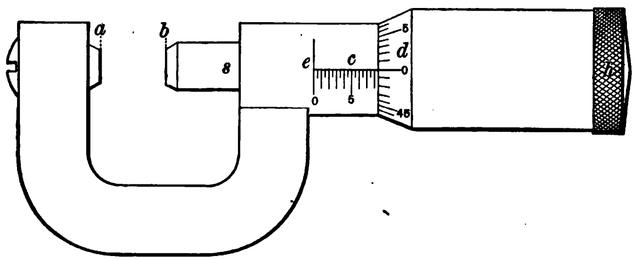


FIG. 7

Never crowd the threads. The zero of the graduated circle should now coincide with the line ec on the scale. If this is not the case, have the instructor adjust the stop a.

Insert the object to be measured between the jaws ab and again turn up the milled head until it slips between the fingers when held with the same pressure as that used to test the zero reading. Read the whole number of millimeters and half millimeters of separation of the jaws upon the scale ec and add the number of hundredths millimeters registered upon d. This is the thickness of the object.

The following illustrates the method of computation:

$D = 2.534$ cm.	$D^2 = 6.421$	$D^3 = 16.27$
2.534	$D = 2.534$	$\pi = 3.142$
10 136	25 684	3 254
76 02	192 63	65 08
1 267 0	3 210 5	1 62 7
5 068	12 842	48 81
$D^2 = 6.421$	$D^3 = 16.27$	$\pi D^3 = 51.12$

$$6\underline{|51.12}$$
$$8.520 \text{ cc.} = \tfrac{1}{6}\,\pi D^3 = \text{Volume}$$

(*b*) *Weight of balls.* Weigh ten or twelve balls all at once on the balances. From the total weight, the number of balls, and the volume of a single ball find the density of steel, i.e. the number of grams in 1 cc. Record thus:

	First ball	*Second ball*	*Third ball*	*Fourth ball*	*Fifth ball*	*Mean*
Diameters:	19.053	19.050	19.048	19.047	19.050	19.050 mm.

∴ Volume of 1 ball = 3.6216 cc. Weight of 12 balls = $341.\underline{0}$ g.
∴ Weight of 1 ball = 28.42 g. ∴ Density of steel = 7.846

II. From weight of spheres and weight of water which they displace. Fill a cylindrical vessel, holding about 150 cc., with water and cover with a ground-glass plate (Fig. 8), carefully excluding all air bubbles. Dry the outside and place on the left pan of the balance. Place on the same pan, beside the vessel of water, the same number of balls used in I, and find the weight of the whole load.

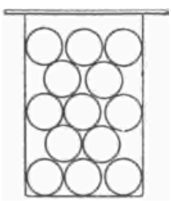


FIG. 8

Remove the vessel of water, lift off the cover, and drop the balls into the water. Replace the cover, dry the outside of the cylinder, replace it on the balance pan, and weigh again. From the two weighings find the weight of the water displaced by the balls. Since 1 cc. of water weighs 1 g., this last weight is, of course, the volume in cubic centimeters

of the displaced water, and this is, of course, the same as the volume of the balls. Find the weight of the balls alone and thence compute the density of steel. Find the per cent of difference between this value and that obtained in I. Record thus:

Weight of 12 balls plus cylinder full of water	= 668.4 g.
Weight of 12 balls in cylinder full of water	= 625.0 g.
Weight of water displaced by balls	= 43.4 g.
Weight of 12 balls alone (from I)	= 341.0 g.
∴ Density of steel	= 7.85
Per cent of difference between results of I and II	= .2

State in your notebook which of the above methods of finding the density of steel you consider the more accurate, giving the reason for your opinion.

EXPERIMENT 4

RESULTANT OF TWO FORCES

I. Parallel forces. Support two spring balances from nails, pegs, or tripod rods, as in Fig. 9, and so choose the distance

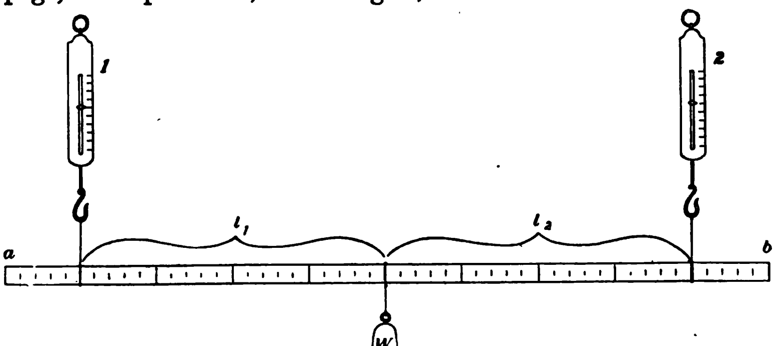


FIG. 9

between the supports that the meter stick *ab* is supported at, say, the 10-cm. and 90-cm. divisions.

Record the readings of the balances *1* and *2* (see figure).

Hang from the 50-cm. mark a mass W which you have already weighed on one of the spring balances, and which is large enough to stretch it nearly to its limit.

Read the balances 1 and 2 and call the differences between these readings and the initial readings F_1 and F_2 respectively.

Then move W successively to the 40-cm., the 30-cm., and the 20-cm. marks, and repeat the readings for each position.

Let l_1 and l_2 represent in each case the distance in decimeters from the point from which W is hung to 1 and 2 respectively. Record as indicated below:

Reading of *1*: without W ———; W at 50 cm. ———; at 40 cm. ———; at 30 cm. ———; at 20 cm. ———.
Reading of *2*: without W ———; W at 50 cm. ———; at 40 cm. ———; at 30 cm. ———; at 20 cm. ———.

F_1	F_2	$F_1 + F_2$	W	$F_1 \times l_1$	$F_2 \times l_2$

State in your notebook what you learn from your results regarding, first, the magnitude of the resultant of two parallel forces; and second, the product of either of the two forces by its distance from the resultant.

II. Concurrent forces. Fasten three spring balances to a small ring *a* by cords about 8 in. long, and slip the rings of the balances over wooden pegs or nails in a board *AB* about 3 ft. square (Fig. 10). Choose such holes for the pegs that each balance is stretched to at least one half of its full range.

Slip a page of your notebook beneath the central ring, fasten it down with thumb tacks or weights, and with a sharp-pointed pencil make a dot on the paper just at the center of the ring. Displace the ring and see that its center comes back exactly to the same position as at first. If this is not the case, the cause probably lies in the friction which exists between the balances and the table top, a difficulty which may be remedied by raising the rings slightly on the pegs.

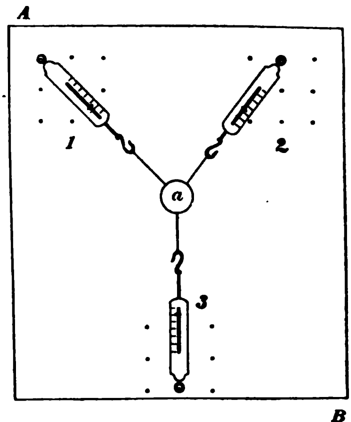


FIG. 10

Make a dot exactly beneath each string and as far from a as possible; then take the three balance readings.

Unhook each balance from its peg and note the reading of the pointer as the balance lies flat on the table. If this reading is less than zero, add the suitable correction to the balance reading recorded on the paper; if it is more than zero, subtract the appropriate amount.

Remove the paper and with great care draw a fine line from the central point through each of the three outside points. The direction of each line will represent the direction of the corresponding force.

Measure off a distance on each line which shall be proportional to the corresponding force, choosing any convenient scale; e.g. if the forces are 700, 1000, and 1200 g., they may be conveniently represented by lines 7, 10, and 12 cm. long.

With any two of these lines as sides complete a parallelogram, using a ruler and compasses to get the sides exactly parallel. Draw the diagonal of this parallelogram from the central point a, measure its length, and find the magnitude of the force which

it represents. Thus, if the diagonal has a length of 134 mm., it would represent in the foregoing illustration a force of 1340 g. Compare with the reading of the third balance. Tabulate thus:

Reading of balance 1 = ——	Correction = ——	$\therefore F_1$ = ——
Reading of balance 2 = ——	Correction = ——	$\therefore F_2$ = ——
Reading of balance 3 = ——	Correction = ——	$\therefore F_3$ = ——
Length of line 1 = ——	of line 2 = ——	
Length of diagonal = ——	∴ Resultant = ——	% error = ——

State in your notebook what you have proved to be true regarding the magnitude and direction of the resultant of two forces which meet at an angle.

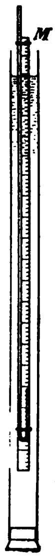


Fig. 11

EXPERIMENT 5

PRESSURE BENEATH THE FREE SURFACE OF A LIQUID

I. Verification of the law of depths and densities.

(*a*) *Measurements in water.* Immerse the manometer *M* of Fig. 11 to the greatest depth possible in the long glass vessel *V* filled with water.[1] A length of at least 1 m. is desirable (see tube of Experiment 40).

Measure the distance from the surface of the water to the top of the mercury in the short arm, and record this distance as the *first depth.* Measure the distance between the two levels of the mercury in the two arms of the manometer, and record this difference as the *first pressure.* (It is often convenient to express pressures in this way, in millimeters of mercury instead of in grams.) Raise the manometer about 5 cm. and make similar measurements. Continue in this way, diminishing the depth about 5 cm. at a time, until the surface is reached.

[1] A piece of glass tubing about 1 m. long, 4 or 5 cm. in diameter, and closed at the bottom with a rubber stopper answers the purpose admirably.

(*b*) *Measurements in gasoline.* Fill the vessel V with gasoline instead of water, and make another set of similar observations.

Tabulate results as follows:

Water			Gasoline		
Depth	*Pressure*	$\frac{Depth}{Pressure}$	*Depth*	*Pressure*	$\frac{Depth}{Pressure}$
—— cm.	—— mm.	——	—— cm.	—— mm.	——
—— cm.	—— mm.	——	—— cm.	—— mm.	——
—— cm.	—— mm.	——	—— cm.	—— mm.	——
etc.	etc.	etc.	etc.	etc.	etc.

II. Graphical representation of a direct proportion. When two quantities are related in the way in which the pressure P and the depth D are seen to be related above, i.e. when making one quantity two, three, or four times as great makes the other two, three, or four times as great, the one quantity is said to be *directly proportional* to the other, or to *vary directly* with the other.

It will be seen, from the third and sixth columns above, that the ratio between the two quantities D and P, which are related in this way, is always constant. Hence, if P_1, P_2, P_3, etc., represent the pressures at depths D_1, D_2, D_3, etc., then

$$\frac{D_1}{D_2} = \frac{P_1}{P_2}, \frac{D_1}{D_3} = \frac{P_1}{P_3}, \text{ etc., } \quad \text{or} \quad \frac{D_1}{P_1} = \frac{D_2}{P_2} = \frac{D_3}{P_3}, \text{ etc.,}$$

or, more simply, $$\frac{D}{P} = \text{constant.}$$

This is the analytic or algebraic way of expressing the fact that D and P are *directly proportional* to each other.

A third way of expressing the relationship between two quantities one of which depends for its value upon the value of the other, is to plot them in a "graph," or curve. To find the nature of the curve which represents the direct proportionality of this experiment, proceed as follows:

Draw two straight lines OX and OY on a piece of squared (coördinate) paper (Fig. 12). Represent pressures by distances

above OX, and depths by distances to the right of OY; e.g. let one space above OX represent a pressure of 1 mm. of mercury, and one space to the right of OY represent a depth of 2 cm. below the surface of the liquid. Any point on the line AB will therefore represent a pressure of 18.5 mm. of mercury, since it is 18.5 spaces above OX; and any point on CD will represent a depth of 25 cm., since this line is 12.5 spaces to the right of OY. The point b at the intersection of these lines therefore represents a pressure of 18.5 mm. and a depth of 25 cm. Similarly, if the table shows that the pressure is 29.6 mm. when the depth is 40 cm., this fact will be represented by the point l, which is 29.6 spaces above OX and 20 spaces to the right of OY, since we have chosen to let one space in the direction OX stand for 2 cm.

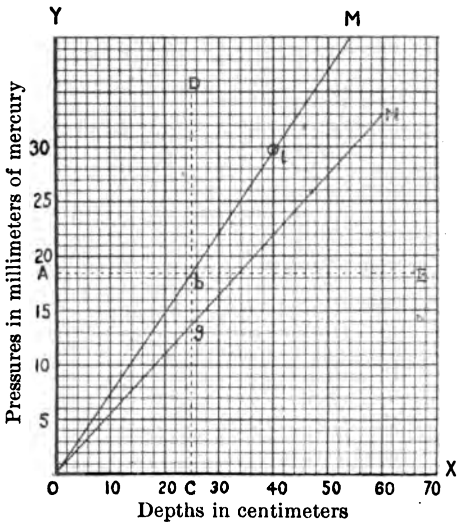


FIG. 12

Find in this way the point corresponding to each depth and its corresponding pressure for the measurements taken in water. These points will be found to lie almost exactly on a straight line OM. With a sharp pencil and a ruler draw through O the straight line which passes as close as possible to all of the plotted points.

In a similar way plot for the readings in gasoline, using the same axes, OX and OY, and the same "scale"; i.e. let one space above OX represent a pressure of 1 mm. of mercury, and

one space to the right of OY represent a depth of 2 cm.[1] These points will be found to lie almost exactly on the straight line ON.

We learn, therefore, that the geometrical or graphical interpretation of a direct proportionality is a straight line.

Divide the pressure Cg, which your graph shows to exist at a given depth in gasoline, by the pressure Cb at the same depth in water. The density of gasoline is about .71. What do you get by this division?

Summarize in the notebook the results of the experiment, stating first in words the law which expresses the relation between *pressure* and *depth*, as proved in the experiment; stating, second, what is the analytic expression of this law; and, third, what is its graphical expression.

State also why dividing Cg by Cb in Fig. 12 gave us the density of gasoline.

EXPERIMENT 6

MEASUREMENT OF PRESSURES BY MANOMETERS

I. Determination of the densities of the liquids used in the manometers. Weigh a glass-stoppered bottle having a capacity of at least 200 cc., first when empty, then when filled with water, and again when filled with gasoline. Subtract the weight of the empty bottle and stopper from each of the last two weights. This gives the weight of equal volumes of water and of gasoline. From these two weights find the *specific gravity* of gasoline, i.e. the ratio between the weights of equal volumes of gasoline and water. This is numerically equal to the density

[1] The scale should always be so chosen that the curve will cover nearly the entire page. Any number of spaces, however, or any fractional part of a space might be used vertically or horizontally to represent a millimeter of pressure or a centimeter of depth.

of gasoline, i.e. the number of grams in 1 cc., since 1 cc. of water weighs 1 g. Record thus:

	Weight of bottle	= —— g.
	Weight of bottle and water	= —— g.
	Weight of bottle and gasoline	= —— g.
∴	Weight of water	= —— g.
∴	Weight of gasoline	= —— g.
∴	Density of gasoline	= ——

II. Determination of the pressure within the bottle B. Arrange two pressure gauges, or manometers, as in Fig. 13, gauge 1 being filled with water, and gauge 2 with gasoline. Force air through O into the bottle B until the *gasoline column* is near the top. Then close with the pinch-cock K the rubber tube which connects the bottle with the outside air.

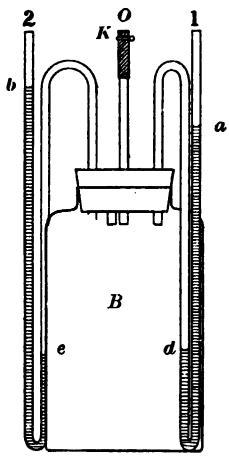


FIG. 13

As soon as the levels of the gauges are stationary measure with a meter stick the height of the liquid surfaces above the table at a, d, b, and e, measuring in each case to the lowest part of the curved liquid surface.

Let h_1 represent the difference in level in centimeters between the points a and d, and let h_2 represent the difference between the points b and e. Let d_1 and d_2 represent the densities of the liquids in 1 and 2 respectively.

From each of the relations $p = h_1d_1$ and $p = h_2d_2$, compute the pressure p, in grams per square centimeter, existing within the bottle, and see how well the two results agree. This will be a check on the correctness of the density determination which you made in I. It need scarcely be said that the pressure acting upon each manometer is necessarily the same, since it is simply the pressure existing within the bottle.

Record the results of your measurements in the following form:

From table to a = —— cm. From table to b = —— cm.
From table to d = —— cm. From table to e = —— cm.
$\therefore h_1$ = —— cm., h_2 = —— cm., h_1d_1 = ——, h_2d_2 = ——
Mean p, in grams per square centimeter, = ——
Per cent of difference between pressure by 1 and 2 = ——

III. Measurement of pressure in city gas mains. Attach K to the gas cock and see how good an agreement you can obtain between the two different measurements of the gas pressure furnished by the two manometers.

Record III exactly as you recorded II.

Answer in your notebook the following questions:

If the manometer tubes had had different diameters, would the results have been different? State reasons.

Can you see in II a ready means of comparing the densities of any two liquids? From your results compare the densities of water and gasoline by this method and see how well the result agrees with that found in I.

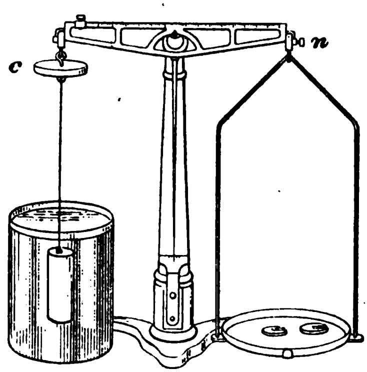


FIG. 14

EXPERIMENT 7

ARCHIMEDES' PRINCIPLE AND THE DENSITY OF A SOLID

I. To test Archimedes' principle for immersed bodies. Remove the left pan from the balance and replace it by the counterpoise c (Fig. 14) which is made as nearly as possible of the same weight as the pan. Adjust the balance by means of the nut n until the pointer stands at

the middle mark. Suspend an aluminum cylinder, or any regular solid body of volume 50 cc. or more, from the left arm of the balance and counterpoise accurately with weights in the opposite pan. Record this weight.

Immerse the cylinder in water, as in Fig. 14. Carefully remove all air bubbles and weigh again. From these observations find the *loss of weight* which the body experiences when immersed in water. Measure the dimensions of the cylinder with the micrometer or vernier calipers or simply by wrapping a fine silk thread about it say thirty times and measuring the length of the thread. Then compute the volume in cubic centimeters.

Compare the *loss of weight* obtained above with the *weight of the liquid displaced* by the body (i.e. the volume of the body times the density of the liquid, which is in this case 1).

Weigh the cylinder when it is immersed in a beaker of gasoline and compare the loss of weight with the weight of the displaced liquid, taking the density of gasoline from the results of Experiment 6 (I).

Record thus:

			Mean
Weight of cylinder in air	=—— g.	Diameters —— —— ——	—— cm.
Weight of cylinder in water	=—— g.	Length =—— cm. ∴ Vol.	=—— cc.
Loss of weight in water	=—— g.	Weight of displaced water	=—— g.
		Per cent of difference	=——
Weight in gasoline	=—— g.	Weight of displaced gasoline	=—— g.
Loss of weight in gasoline	=—— g.	Per cent of difference	=——

State in your notebook in your own words the principle which your experiment has shown to be true.

II. To find the density of a solid heavier than water by loss of weight method. Since density is defined as $\frac{\text{mass}}{\text{volume}}$, it is obvious that the most direct way of determining the density of any regular solid is to find its mass by a weighing and its volume by direct measurement. But it would evidently be quite

impossible to find in this way the density of an irregular body, like a lump of coal, because of the difficulty of measuring its volume. The principle discovered in I, however, furnishes a very simple way of finding this volume, since it is only necessary to find the loss of weight which the body experiences in water, in order to find the weight of an equal volume of water, and this is the same as the volume of the body, since the density of water is 1. We have, then,

$$\text{Density} = \frac{\text{weight in air}}{\text{loss of weight in water}}.$$

Without making any additional measurements, find the density of the body used in I, (*a*) by dividing the weight in air by the volume as there computed from its dimensions, and (*b*) by dividing the weight in air by the volume of the cylinder as found from the loss of weight in water.

Find in the latter way the density of some irregular body, — for example, a brass weight.

Record thus:

(*a*) Density of aluminum = mass ÷ volume from dimensions			= ——
(*b*) Density of aluminum = mass ÷ volume from loss of weight			= ——
		Per cent of difference	= ——
Weight of brass body in air	= —— g.;	weight in water	= ——
∴ Density of brass	= ——.	Accepted value	= 8.4

EXPERIMENT 8

ARCHIMEDES' PRINCIPLE AND THE DENSITY OF A LIQUID

I. To test Archimedes' principle for floating bodies. Place in a deep vessel of water (see Fig. 11, p. 14) a piece of thin-walled, cylindrical glass tubing about three quarters of an inch in diameter, twenty-four inches long, and loaded with shot at the lower

end (Fig. 15). (For the sake of convenience in II it is best to load the tube first in a vessel of gasoline until it sinks to within say 2 cm. of the top and then to transfer it without change in the load to the vessel of water.) Place a rubber band about the tube at the exact point to which it sinks. Remove the tube from the water, wipe it dry, and then weigh it with the contained shot. Measure the diameter of the tube in four or five different places, and the distance from the rubber band to the bottom. From these two measurements compute the volume, and therefore the weight, of the water displaced by the floating body. Record thus:

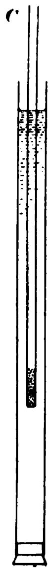


FIG. 15

First diam.	=—— cm.	Length immersed	=—— cm.
Second diam.	=—— cm.	Area of cross section	=—— sq. cm.
Third diam.	=—— cm.	Weight of displaced water	=—— g.
Fourth diam.	=—— cm.	Weight of tube and shot	=—— g.
Mean diam.	=—— cm.	Per cent of difference	=——

Infer from your results the general law of flotation and state it in your notebook.

II. Density of a liquid by the principle of flotation. (*a*) *Constant-weight hydrometer.* Immerse the tube with its contents in a vessel of gasoline. Since the tube will float only when the weight of the displaced liquid is equal to the weight of the floating body, and since gasoline is less dense than water, the tube must sink to a greater depth in the lighter liquid than it did in water, e.g. to some point C. Place a rubber band at this point, and then remove and measure the length immersed.

If l_1 is the length of the tube immersed in water and l_2 the length immersed in gasoline, then the density of gasoline must be l_1/l_2 times the density of water; for if A represents the area of the cross section of the tube, the weight of the water displaced by the tube is Al_1; and if d is the density of gasoline,

the weight of the displaced gasoline is Al_2d; and since these weights are equal, being both equal to the weight of the floating body, we have $Al_2d = Al_1$, i.e. $d = l_1 / l_2$.

Test the correctness of your result by means of a commercial constant-weight hydrometer (see Fig. 16).

(*b*) *Constant-volume hydrometer.* Drop shot into a test tube which has been drawn out to the shape shown in Fig. 17 until, when immersed in gasoline, it sinks to the mark *a* on the narrow part of the stem. Remove the tube, dry, and weigh with the contained shot. Immerse in water, add more shot until the tube sinks to the same mark, remove, dry, and weigh again. The volume of the liquid displaced is the same in the two cases, and the weight of this volume is equal to the weight of the tube and its contents. The specific gravity or density of the gasoline may therefore be found at once, since the data are available for finding the weight of a given volume of gasoline and the weight of an equal volume of water. Compare the results with those obtained in (*a*). Record as follows:

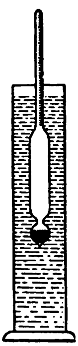


FIG. 16

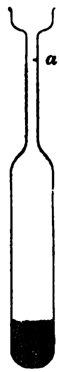


FIG. 17

(a)		(b)	
Length in water	= —— cm.	Weight in water	= —— g.
Length in gasoline	= —— cm.	Weight in gasoline	= —— g.
Density of gasoline	= ——	Density of gasoline	= ——
By hydrometer of Fig. 16	= ——	Diff. between (*a*) and (*b*)	= ——
Per cent of difference	= ——	Per cent of error	= ——

State in your notebook what two general methods you have discovered for finding the densities of liquids.

Can you see any reason why a constant-weight hydrometer made with a narrow stem (Fig. 16) is a much more accurate instrument for determining the densities of liquids than a cylindrical constant-weight hydrometer like that shown in Fig. 15?

If any convenient solid is weighed first in air, then in water, and then in some other liquid, e.g. gasoline, the three weighings will furnish data for determining the density of gasoline. Write an explanation of this in your notebook, and compute the density of gasoline from the weighings of this sort which you made in Experiment 7.

EXPERIMENT 9

DENSITY OF A SOLID LIGHTER THAN WATER

I. By weighing first in air and then when immersed in water with the aid of a sinker. If a body is lighter than water, the weight of an equal volume of water may be obtained with the aid of a sinker. Use a wooden block *B* (Fig. 18) which has been paraffined so as to prevent the absorption of water. Weigh the block in air and then with the sinker attached, the block being in air and the sinker *S* in water, as shown in the figure. Lastly, weigh when the block and sinker are both under water. The difference between the second and third weighings is evidently the buoyant effect of the water on the block alone, i.e. it is the weight of the water displaced by the block, and hence it is also the volume of the block. From this difference and the weight of the block in air obtain the density of the wood. Record thus:

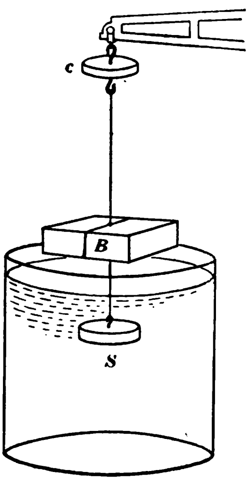


FIG. 18

Weight of block alone in air	= —— g.
Weight when block is in air and sinker in water	= —— g.
Weight when both block and sinker are in water	= —— g.
∴ Density of wood	= ——

Explain in your notebook how you calculated the density of wood and why your method of procedure gives this density.

II. From weight, length, breadth, and thickness of block. Measure the three dimensions of the block with a meter stick held on edge, as in Fig. 2. From these measurements and the weight of the block, obtained in I, compute the density of the wood. Record thus:

Length of block	= —— cm.	∴ Volume = —— cm.
Height of block	= —— cm.	∴ Density = ——
Thickness of block	= —— cm.	% of difference in I and II = ——

III. From the depth to which the block sinks in water. Wax a pin to the end of a metric rule *ab*, arranged as in Fig. 19, and take the reading of the point on this rule at which it meets the straight edge *CD* when the pin point just touches the corner *m* of the floating block. Then take the reading on *ab* when the pin point just touches the surface of the water, say 1 cm. away from the edge of the block. The difference between these two readings subtracted from the thickness of the block would give the distance

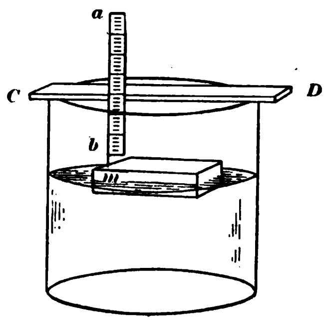


FIG. 19

which the block sinks in the liquid, if the surface of the block were accurately horizontal. In order to obtain as accurate a value as possible for this distance, repeat the measurements at each corner of the block, and take a mean of these four differences. From this mean difference find the distance h' which the block sinks in water. Then, from h' and the thickness h of the block, compute its density d from the relation

$$d = \frac{h'}{h}.$$

Record the results of your observations thus:

	First corner	*Second corner*	*Third corner*	*Fourth corner*
Reading with pin touching water =	—— cm.	—— cm.	—— cm.	—— cm.
Reading with pin touching block =	—— cm.	—— cm.	—— cm.	—— cm.
Differences =	—— cm.	—— cm.	—— cm.	—— cm.

Mean difference = —— h = —— $\therefore h'$ = —— $\therefore d$ = ——

Prove in your notebook that the above equation for the density of the block, namely $d = \frac{h'}{h}$, follows at once from the statement of Archimedes' principle as applied to floating bodies, viz. "The weight of the floating body is equal to the weight of the liquid which it displaces." (Remember that weight = volume $\times$ density; so that, if A represent the area of the top of the block, the weight of the block is Ahd, while the weight of the displaced liquid is $Ah'd'$, d' in this case being 1.)

Can you see from your analysis any general relation which must always exist between the density of a body floating on water, the volume of the body, and the fraction of the volume which is beneath the surface?

EXPERIMENT 10

THE RELATION BETWEEN THE PRESSURE AND VOLUME OF A GIVEN MASS OF GAS AT CONSTANT TEMPERATURE

I. Verification of Boyle's law. The object of this experiment is to vary the volume of a small quantity of air AD (Fig. 20, 1), confined in a barometer tube, by varying the pressure to which it is subjected, and to find how this volume changes as we double, treble, quadruple, etc., the pressure.

First read the barometer and record its height in centimeters; then, by means of a clamp C, hold in the position 1 (Fig. 20) a

barometer tube which is closed at the upper end and open at the lower end, and which contains a mercury column *AB* and the thread of air *AD*.[1] Measure carefully the length *AD* of the

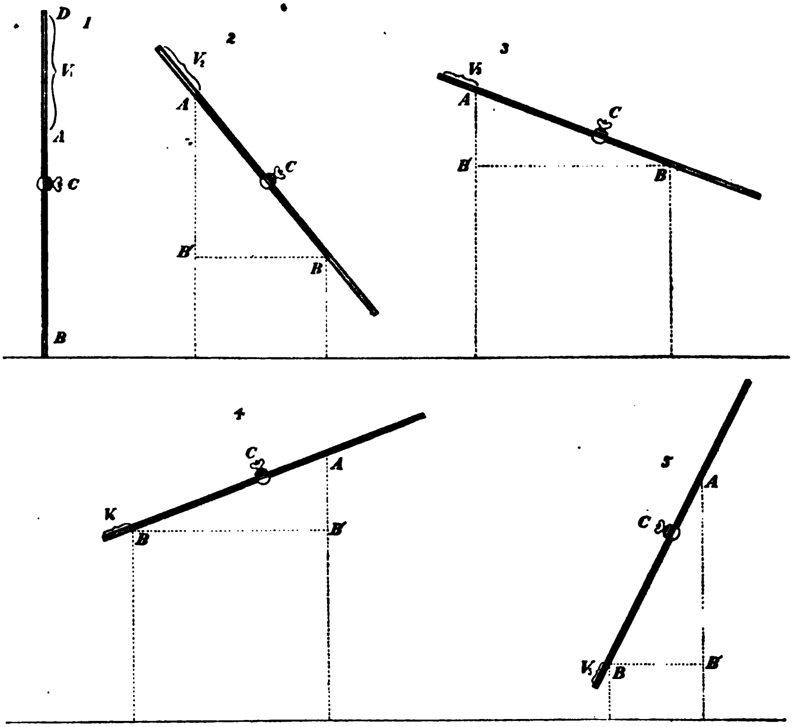


FIG. 20

confined body of air. Since the cross section of the tube is everywhere the same, the *volume* of the confined air will always be proportional to its length; hence we shall call the length *AD* volume 1, and shall denote it by V_1.

[1] To construct tubes of this sort pieces of barometer tubing should be chosen which are from 1 mm. to 1.5 mm. in bore and 110 cm. long. They should be cleaned by pouring through them a hot solution of potassium bichromate in

Next measure the length of the mercury column AB in centimeters. The barometric height minus this length AB is obviously the pressure, measured in centimeters of mercury, to which the air V_1 is subjected. Call this pressure P_1.

Incline the tube slowly until the volume V_2 (see Fig. 20, 2) of the inclosed air is one half of the original volume V_1. Now measure the heights of the points A and B above the table and subtract the difference AB' from the barometric height, thus getting P_2, the pressure corresponding to the volume V_2. (The reason for this procedure will be clear when it is remembered that pressure in liquids depends simply upon *difference in horizontal levels.*[1])

Place the tube successively in positions 3, 4, 5 (see Fig. 20) such that the volume of the inclosed air shall be 1/3, 1/4, 1/5, and, if possible, 1/6 of the original volume. Measure in each case the heights of the ends A and B of the mercury column from the table top and compute the pressures corresponding to each volume. (Remember that the pressure on the confined air is *less* than the barometric pressure if the open end of the tube is *lower* than the closed end, and *greater* than the barometric pressure if the open end is *above* the closed end.)

strong sulphuric acid. They should then be rinsed first with distilled water, then with clean alcohol, and finally dried with a current of air from a bellows. These tubes may be filled by sinking them in a larger tube containing perfectly clean mercury until the mercury rises in the capillary bore to within 12 or 15 cm. of the top, and then sealing the top with hard wax and withdrawing; or, again, the tube may be laid horizontally and a piece of gum tubing attached to one end and clean mercury poured into this tubing until it approaches to within 5 or 6 cm. of the other end, when the sealing should be done.

[1] The proof that this is indeed the case is found in the familiar fact that water will stand at the same level in two vessels connecting at the bottom and consisting, the one of a long inclined tube, the other of a short vertical one. If the pressure at the bottom of the longer tube were the greater, the water would, of course, have to stand higher in the shorter tube.

Record as follows:

POSITION	VOLUME OF CONFINED AIR	HEIGHT OF A ABOVE TABLE	HEIGHT OF B ABOVE TABLE	DIFFERENCE	BAROMETRIC HEIGHT	PRESSURE	PRESSURE TIMES VOLUME	DIFFERENCE FROM MEAN PV
1								
2								
3								
4								
5								

$V_2/V_1 =$ —— $V_3/V_1 =$ —— $V_4/V_1 =$ —— $V_5/V_1 =$ —— $V_6/V_1 =$ ——
$P_1/P_2 =$ —— $P_1/P_3 =$ —— $P_1/P_4 =$ —— $P_1/P_5 =$ —— $P_1/P_6 =$ ——
Error = —— —— —— —— ——

II. Graphical representation of an inverse proportion. When two quantities are related in the way in which P and V are found to be related above, i.e. when making P two, three, or four times as great makes V 1/2, 1/3, or 1/4 as great, one quantity is said to be *inversely proportional* to the other, or to vary *inversely* with the other. It will be seen from the next to the last column that the product of two quantities which vary in this way is always *constant*. Hence, if P_1, P_2, P_3, etc., represent the pressures corresponding to the volumes V_1, V_2, V_3, etc., then

$$\frac{P_1}{P_2} = \frac{V_2}{V_1}, \quad \frac{P_1}{P_3} = \frac{V_3}{V_1}, \text{ etc., or } P_1V_1 = P_2V_2 = P_3V_3 = P_4V_4,$$

or, more simply, $PV =$ constant.

This is the analytic or algebraic way of expressing the fact that P and V are inversely proportional to each other.

To find the graph or curve which represents an inverse proportion, plot on a sheet of coördinate paper, precisely as in

Experiment 5, the pressures in the table above as horizontal distances and the corresponding volumes as vertical distances. Utilizing the law discovered experimentally above, compute the pressures which would correspond to two, three, and four times the original volume, and the volumes corresponding to two, three, and four times the greatest pressure, and plot as part of the same curve not only the points corresponding to the observed values but also those corresponding to these computed values of the pressure and volume. Select your scale so that the curve will just nicely fill a sheet of coördinate paper.

This curve is an *hyperbola.* Its two arms approach nearer and nearer to the axes OX and OY, but the curve can never touch these arms, for no matter how great the pressure may become, the volume will never become zero, and no matter how great the volume may become, the pressure will never be quite zero. The lines which an hyperbola approaches indefinitely, without ever exactly reaching, are called the *asymptotes* of the hyperbola. In this case the asymptotes are the coördinate axes OX and OY.

Summarize in the notebook the results of the experiment, stating first in words the relation which has been found to exist between pressure and volume, then expressing this relation in the form of an equation, and then stating what sort of curve the experiment has shown to be the graph of this type of relationship.

EXPERIMENT 11

COOLING BY EVAPORATION; SATURATION; DEW-POINT; FREEZING BY EVAPORATION

I. Cooling by evaporation. Let three 4-oz. bottles, one half full of ether, one half full of alcohol, and one half full of water, be provided. The bottles should be closed with small corks and

should have been standing in the room long enough to acquire room temperature.

Holding a thermometer by a string attached to the upper end, swing it back and forth through the air until its reading is constant. Record this reading as the room temperature. Insert the thermometer in the ether bottle, pushing the bulb down beneath the surface of the liquid. After half a minute record the reading as the temperature of the ether in the closed bottle. In the same way take the temperatures of the alcohol and water.

Pour into small porcelain evaporating dishes enough of each liquid to cover the bulb of the thermometer. Pour about the same amount of ether into an open test tube (or the metal tube of Fig. 21), and set it aside in a beaker or other convenient support. Place the thermometer in the evaporating dish which contains the ether, and, keeping the stem inclined so that the bulb is always covered, watch the temperature until it ceases to change, and then record. Take in succession the temperatures of the alcohol and of the water in the evaporating dishes, and of the ether in the test tube. Record thus:

Temperature in room	= ——
Temperature in bottle of ether	= ——
Temperature in bottle of alcohol	= ——
Temperature in bottle of water	= ——
Temperature of ether in evaporating dish	= ——
Temperature of alcohol in evaporating dish	= ——
Temperature of water in evaporating dish	= ——
Temperature of ether in test tube	= ——

State in your notebook what effect your experiments have shown evaporation to have upon the temperature of the evaporating body. Explain, if you can, why the temperature of the ether in the test tube was different from that in the evaporating dish. Put a drop of ether, of alcohol, and of water upon the hand and notice the order in which they disappear. Explain

with the aid of this experiment and the answer to the first question why the ether in the evaporating dish had a lower temperature than the alcohol, and the alcohol a lower temperature than the water.

When a body is below room temperature it is continually receiving heat from the room. When the liquids in the evaporating dishes had reached a constant temperature, what relation existed between the amount of heat which they lost per second by evaporation and the amount which they received per second from the room?

II. Saturation. From the above readings of the room temperature and the temperature of the liquids in the closed bottles, can you draw any inference as to whether or not any evaporation was going on from the surfaces of the liquids in the closed bottles? A space in which evaporation will no longer take place from the surface of a given liquid placed within the space is said to be *saturated* with the vapor of the liquid. This means simply that the space already contains as much of the vapor of the liquid as it is capable of holding at the given temperature.

Cover the bulb of the thermometer with a bit of absorbent cotton, dip it into the bottle of ether, and then lift it so that the bulb and cotton are above the surface of the ether, but still in the bottle. Watch the temperature for a minute or two, and then record. Transfer the covered bulb from the bottle to the test tube and hold it there above the surface. After a minute or two record the temperature. Lift the covered bulb out into the air and record the temperature after it has become constant. What do you learn from this experiment regarding the temperature which a thermometer surrounded with a cloth soaked in a liquid will maintain in a space which is saturated with the vapor of the liquid? in a space which is partially saturated? in a space which is free from this vapor, i.e. which is dry?

Wrap some fresh cotton about the bulb of the thermometer, and dip it into the bottle of water; then remove the thermometer and swing it in the room until its reading becomes constant. Record. Would this reading be any different if there were no water vapor already in the room? What would it be if the air were already saturated with water vapor? Can you see, then, how the difference between the readings of a thermometer whose bulb is kept dry and one whose bulb is kept moist gives us some information regarding the dryness of the atmosphere?

III. Dew-point. The amount of vapor which a given space can hold is found to decrease rapidly as the temperature decreases. Hence, if we lower the temperature of a space which is already saturated with any vapor, a part of it condenses. If we lower the temperature of a space which is not saturated, but which contains some vapor, nothing happens until the temperature is reached at which the amount of vapor which already exists in the space is the amount which saturates it. Then condensation begins. *The temperature at which water vapor begins to condense out of the atmosphere as the temperature is lowered, is called the dew-point.* It varies of course from day to day, depending upon how much water vapor exists in the atmosphere.

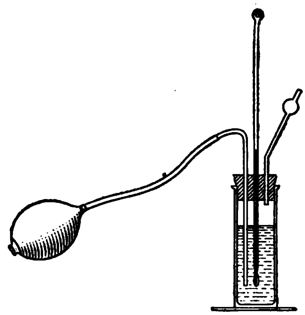


FIG. 21

Fill the polished metal tube[1] of Fig. 21 two thirds full of ether, and force air very gently through it by squeezing the bulb.

[1] This experiment can be performed with almost as good success by simply dropping bits of ice slowly into water contained in a polished vessel, and noting the temperature at which, with continual stirring, the cloud appears on the outside. If the dew-point is below zero, salt should be added bit by bit to the iced water until the cloud appears.

This process facilitates cooling, since it increases enormously the evaporating surface, every bubble having a large surface into which evaporation can take place. The temperature existing within the tube when the first cloudiness begins to appear upon the polished surface is the dew-point, for it is the temperature at which the layers of air in contact with the tube become saturated and begin to deposit their moisture. As soon as this cloudiness is noticed take the reading of the thermometer,

$t°$ C.	P	$t°$ C.	P	$t°$ C.	P
− 10°	2.2	5°	6.5	19°	16.3
− 9°	2.3	6°	7.0	20°	17.4
− 8°	2.5	7°	7.5	21°	18.5
− 7°	2.7	8°	8.0	22°	19.6
− 6°	2.9	9°	8.5	23°	20.9
− 5°	3.2	10°	9.1	24°	22.2
− 4°	3.4	11°	9.8	25°	23.5
− 3°	3.7	12°	10.4	26°	25.0
− 2°	3.9	13°	11.1	27°	26.5
− 1°	4.2	14°	11.9	28°	28.1
0°	4.6	15°	12.7	29°	29.7
1°	4.9	16°	13.5	30°	31.5
2°	5.3	17°	14.4	35°	41.8
3°	5.7	18°	15.3	40°	54.9
4°	6.1			45°	71.4

and then stop the current and notice the temperature at which the cloudiness disappears. Take pains in these experiments not to breathe upon the polished surface. Repeat the whole operation until the temperatures of appearance and disappearance do not differ by more than 1°. Take the mean of the two temperatures as the dew-point.

From the dew-point and the accompanying table find the *humidity* of the atmosphere. This is the ratio between the amount of moisture in the atmosphere at the time of the experiment and the total amount which it is capable of holding

at the temperature of the room. It is found by dividing the pressure of saturated water vapor at the temperature of the dew-point by the pressure of saturated water vapor at the temperature of the room (see table on page 34).[1]

IV. Freezing by evaporation. Place a few drops of water upon the table and set the polished metal tube containing ether upon it. Force air through the ether rapidly and see if you can freeze the tube to the table.

EXPERIMENT 12

RELATION BETWEEN FORCE ACTING UPON AN ELASTIC BODY AND THE DISPLACEMENT PRODUCED

(Hooke's law)

I. Stretching. Set up a steel spring *S* and mirror scale *M*, in the manner shown in Fig. 22.

Take the reading of the index upon the scale when only the weight holder hangs from the spring. In so doing place the eye so that the image of the tip of the pointer *p*, as seen in the mirror, is exactly in line with the tip of the pointer itself. Record the position at which the line of sight crosses the mirror scale, reading to the nearest tenth millimeter (this tenth millimeter place being, of course, an estimate).

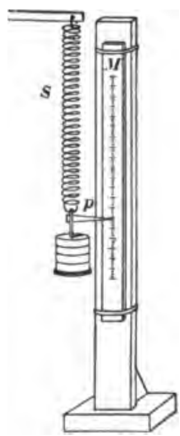


FIG. 22

Increase the weight upon the pan 100 g. at a time until it has reached a total of 400 g., and take the reading on the scale after each addition.

Then remove the weights 100 g. at a time and take the corresponding readings.

Tabulate results as indicated on page 36.

[1] The table shows the pressure P, in millimeters of mercury, of water vapor saturated at temperature $t°$ C.

II. Bending. Set up the mirror scale behind the middle of a thin wooden or steel rod supported as in Fig. 23, and take

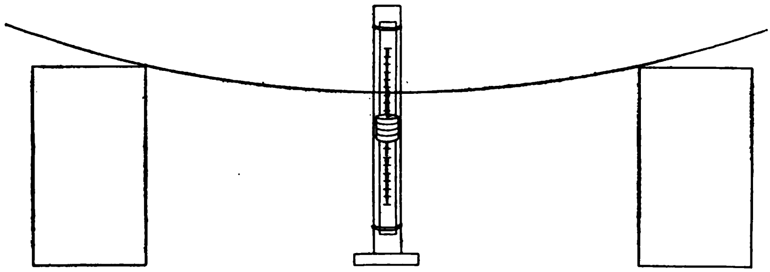


FIG. 23

again a set of readings like those in I, the index being now the point of a pin stuck with wax to the middle of the rod.

Tabulate results of all observations as follows :

Spring		*Differences*	*Rod*	*Differences*
Pan reading	=——		——	
100-g. reading	=——	——	——	——
200-g. reading	=——	——	——	——
300-g. reading	=——	——	——	——
400-g. reading	=——	——	——	——
300-g. reading	=——	——	——	——
200-g. reading	=——	——	——	——
100-g. reading	=——	——	——	——
Pan reading	=——	——	——	——

State in your own words in the notebook the law which the above study of two different sorts of elastic displacement has shown to exist between the distorting force F and the displacement D which this force produces.

State this result in the form of an equation.

Finally, put the results of each experiment into *graphical* form, letting one space in the direction OY (see Fig. 12) represent 15 mm. of displacement from the "pan reading," and one space in the direction OX, 10 g. of weight added to the

pan. For each set of observations draw with a ruler straight lines which shall come as near as possible to touching all the points located.

EXPERIMENT 13

COEFFICIENT OF EXPANSION OF AIR

A and B in this experiment are intended as alternatives, the choice depending upon equipment. It is interesting, however, to have a part of the class perform A and a part B, and then to let them compare results.

A. **Pressure coefficient of expansion.** When a body of gas is heated in a closed vessel the volume of which is kept constant, the pressure which the gas exerts against the walls of the vessel increases as the temperature rises. The ratio between the increase in pressure per degree and the pressure which the gas exerts at 0°C. is called the *pressure coefficient of expansion of the gas.* For example, if P_t represents the pressure at a temperature of t°C. and P_0 the pressure at 0°C., then the increase in pressure has been $P_t - P_0$, the increase per degree has been $\frac{P_t - P_0}{t}$, and the pressure coefficient c is this increase divided by P_0. Thus,

$$c = \frac{P_t - P_0}{P_0 t}.$$

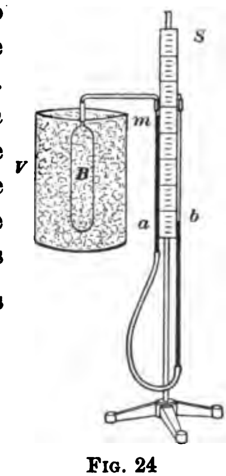


FIG. 24

To find this coefficient experimentally, first read the barometer. Then, before attaching the bulb B, adjust the arms a and b (Fig. 24) until the mercury in each stands, say, 5 cm. above the bottom of the scale S, the distance from the bottom of S to the point of attachment of the rubber tubing to the arm b being at least 30 cm., and the distance from

the mercury surface in *a* to the scratch *m* on the tube *a* being about 4 cm.

See that a few drops of concentrated sulphuric acid are inserted in *B* in order to keep the inclosed air perfectly dry; then attach *B* as in the figure, with a bit of thick-walled gum-rubber tubing, and pack wet snow or crushed ice about it in a vessel *V* until *B* is completely covered.

Raise the arm *b* until the mercury in *a* is just opposite the scratch *m*, tapping *a* gently with a pencil to prevent sticking of the mercury. Wait two or three minutes to make sure that the air in *B* has reached the temperature of the ice, and then adjust again to the scratch *m* and read on the scale *S* the levels in both *a* and *b*.

Put the bulb into the steam generator shown in Fig. 25, and boil the water. Adjust the arm *b* until the level in *a* is again at *m*; tap and again read the level of the mercury in *b*.

Immediately after this reading lower the arm b to its first position, so that the mercury may not be drawn over into B as the bulb cools.

The difference between the two readings in *b* represents the increase in the pressure exerted by the gas in *B* as the temperature was raised from 0°C. to 100°C.; i.e. this difference is $P_t - P_0$ of our equation, t being in this case 100°. The pressure in *B* at 0°C., namely P_0, is simply the barometric height less the difference between the mercury levels in *a* and *b* at zero.

Record your results in systematic form, including a statement of the per cent by which your result differs from the accepted value of this constant, namely .00367, or 1/273.

State in your own way in your notebook exactly what this quantity is which you have found above, and which you call the "pressure coefficient of expansion."

What per cent of error would have been introduced into your numerator, $P_{100} - P_0$, and therefore into your result by an error of half a millimeter in reading either of the levels in *b*?

If the boiling point of water on the day of your experiment were 99.5°, instead of 100°, what per cent of error would you have introduced into your result by calling it 100°? On the whole, is your result as accurate as you could have expected in view of such sources of error as you can see?

B. **Volume coefficient of expansion.** When a confined body of gas is kept under constant pressure and heated, it follows, from Boyle's law, that its volume must increase at the same rate at which its pressure would increase if the volume were kept constant. The ratio between the increase in volume per degree and the volume at 0°C. is called *the volume coefficient of expansion;* i.e. if V_{100} and V_0 represent the volumes at 100°C. and 0°C. respectively, then the volume coefficient c is given by the equation

$$c = \frac{V_{100} - V_0}{100\,V_0}.$$

This coefficient may be defined as *the expansion at 0° C. per cubic centimeter per degree.* It should be the same as the pressure coefficient discussed above.

To find it experimentally let a thread of dry air about 23 cm. long be confined by a mercury index 2 cm. or 3 cm. long in a piece of barometer tubing which is sealed at one end and is about 40 cm. long.[1]

First measure carefully and record the length of the index and the total length of the bore, allowing as best you can for the fact that the bore is not quite uniform very near the closed end.

[1] To make such tubes take barometer tubing of 1.5-mm. bore, clean it with hot aqua regia, or a hot solution of potassium bichromate in strong sulphuric acid, then rinse with distilled water, and dry by gently heating while a current of air passes first through a calcium chloride drying tube, and then through the barometer tube. By sucking through the drying apparatus draw a thread of mercury about 2 cm. long into one end of the tube, shake it to within 23 cm. of the other end, and then detach from the drying apparatus and quickly seal this latter end in a Bunsen flame.

Then stand the tube upright, closed end down, in a battery jar, and pack wet snow about it up to the index. Tap the tube with a pencil, and then measure from the top of the tube to the top of the index. Remove the tube and push it through the hole in the cork which closes the steam generator of Figs. 25 and 36. After the steam has been issuing from the upper vent for a minute or two, adjust the height of the tube in the cork so that the upper end of the index is just on a level with the top of the cork, and then measure from the top of the tube to the top of the cork. Since the tube is of approximately uniform bore, you may take the difference between the last two measurements as $V_{100} - V_0$. From the first three readings find the length of the thread of air at 0°C. and call it V_0. The following are typical observations made by a student.

Length of index	= 18.0 mm.
Length of bore	= 476.5 mm.
From top to index at 0° C.	= 251.0 mm.
From top to index at 100° C.	= 174.5 mm.
$\therefore V_{100} - V_0 = (251. - 174.5)$	= 76.5 mm.
$V_0 = 476.5 - (251. + 18)$	= 207.5 mm.
$\therefore c$	= .00369.
Per cent of departure from accepted value (.00367)	= .6.

Is your error larger than would be accounted for by an error of, say, 1 mm. in measuring $(V_{100} - V_0)$?

If so, it is probable either that the bore is not uniform, or else that the confined air is not thoroughly dry.

EXPERIMENT 14

COEFFICIENT OF EXPANSION OF BRASS

The coefficient of expansion of a solid is equal to that fractional part of its length which it increases when heated 1°, i.e. it is the expansion per centimeter per degree. Thus, if l_2

represent the length at a temperature t_2, and l_1 at a temperature t_1, the coefficient k is given by

$$k = \frac{l_2 - l_1}{l_1(t_2 - t_1)}.$$

It may be determined experimentally by the apparatus shown in Fig. 25.

A shallow transverse groove is filed at some point *c* (Fig. 25) near one end of a piece of brass tubing about a meter long and a centimeter in diameter.

Place the tube upon two wooden blocks *A* and *B*, so that the groove rests upon a sharp metal edge attached to *A*, while the

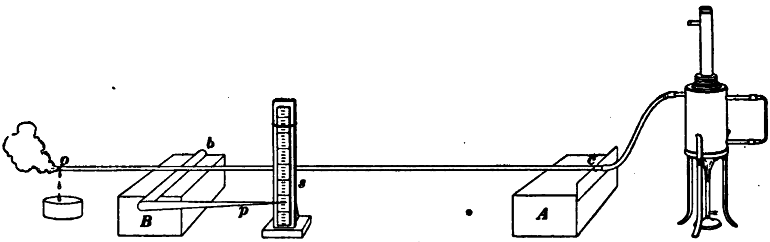


FIG. 25

other end is supported by a piece of glass or brass tubing *b* about 6 mm. in diameter, which in turn rests upon a smooth glass plate waxed to the top of *B*. To one end of the glass rod *b* is attached by means of sealing wax a pointer *p* about 20 cm. long. When the brass rod is heated its expansion causes *b* to roll forward, and this produces a motion of the end of the pointer *p* over the mirror scale *s*.

Attach the tube, as in the figure, to a steam boiler containing at first only cold water. Then insert a thermometer into the open end *o* of the brass tube.

Give the thermometer three or four minutes to take up the temperature of the tube; then read, record, and replace it in *o*.

Record the position of the *tip* of the pointer upon the mirror scale, estimating very carefully to tenths of a millimeter. In taking this reading sight (as always) across the image of the pointer and the pointer itself.

Apply heat to the boiler until steam passes *rapidly* through the tube. If the current of steam is sufficiently strong, the brass tube will not need a nonconducting covering. Nevertheless it is generally advisable before beginning the experiment to roll up a paper tube about $1\frac{1}{2}$ cm. in diameter, and to slip it over the tube between *c* and *b* in order to minimize heat losses.

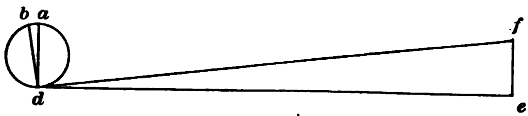


FIG. 26

After steam has been issuing from *o* for one or two minutes, take again the reading of the pointer *p* upon the scale *s*.

Take the reading of the thermometer as it lies in the tube surrounded by the steam escaping from *o*.

Measure with a meter stick the distance between the knife-edge *c* and the middle of the rod *b*.

Measure also with the meter stick the length of the pointer *p* from its tip to the middle of *b*.

Measure with the micrometer caliper the diameter of *b*, taking readings upon at least three different diameters. This measurement should be made to within a hundredth of a millimeter at the least. If the calipers are not available, wrap a fine linen thread ten or twenty times around *b*, measure the length of the thread, and from this compute the diameter.

To find the amount of expansion of the brass tube, divide the difference in the pointer readings on *s* by the ratio of the length of the pointer to the diameter of the glass rod. The reason for this can be seen from Fig. 26. At any given instant the rod is rotating about its lowest point *d*. The line *ef* represents the

distance through which the end of the pointer moves while the top of the rod is moving through a distance ab; but from similar triangles

$$\frac{ab}{ad} = \frac{ef}{de}, \quad \text{i.e.} \quad ab = ef \div \frac{de}{ad}.$$

From the expansion of the brass tube, its length between c and b, and its change in temperature, compute the coefficient of expansion of the tube, i.e. the fractional part of its own length by which that part of the tube between c and b expands when heated 1°C.

If time permit, take out the brass tube, cool it with tap water to about the temperature of the room, and repeat the experiment. Take the mean of the two trials as the value of k.

In calculating be sure that you express all length measurements in the same units, i.e. all in centimeters, or all in millimeters; not part in centimeters and part in millimeters.

Tabulate as follows:

Trial	*First temperature of rod*	*Second temperature of rod*	*Difference*	*First reading on s*	*Second reading on s*	*Difference*	*Length of cb*	*Diameter of b*	*Coefficient*
1	——	——	——	——	——	——	——	——	——
2	——	——	——	——	——	——	——	——	——

Mean value of k = ——
Accepted value = .0000187
Per cent of error = ——

Express in words the equation on page 41.

What per cent of error did you introduce into the measurement of the motion of the pointer over the scale, if you made a mistake of 0.2 mm. in estimating either position of the pointer?

What per cent is introduced into the result if the mean temperature of the tube is 1° lower than that of the steam?

Are these errors greater or less than the observed error?

EXPERIMENT 15

THE PRINCIPLE OF MOMENTS

Slip the meter bar *AB* through the sliding knife-edge support *C* (Fig. 27) until it will rest exactly horizontally when the knife-edge rests upon the glass surfaces of the wooden frame *f*. See that *C* is clamped firmly to the bar, read the position of the knife-edge on the bar, and then proceed as follows.

(*a*) By means of thread hang a 100-g. weight W_1 from a point near one end of the beam and find the point at which a 200-g.

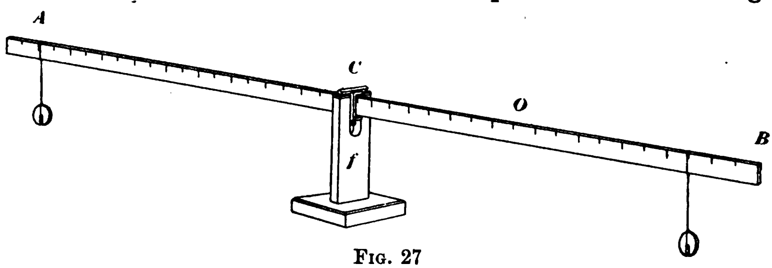


FIG. 27

weight W_2 must be hung on the other side in order that the bar may rest again exactly horizontally. Take the product of each weight by its distance from the fulcrum. What relation do you discover between these two moments? (The product of a force by the lever arm on which it acts is called the "moment" of the force.)

(*b*) Change one of the weights and again compare the moments.

(*c*) Hang two weights, say a 100-g. weight W_1 and a 50-g. weight W_2, at different points on the left side of the fulcrum and not too close to it, and then balance the lever by hanging a 200-g. weight W_3 at the proper point on the other side. Compare the sum of the moments of the first two forces with the moment of the second.

(*d*) Hang some unknown weight X from a point near the left end at a distance l from the fulcrum, and balance it by a known weight W hung at the proper point on the other side. By applying the principle of moments, which you learned in (*a*), (*b*), and (*c*), find the value of X. Weigh it on the balance and compare the two results.

(*e*) Hang from different points on the right side an unknown weight X and a known weight W_1, and balance by two known weights W_3 and W_4 placed at different points on the other side. Let l represent the distance of X from the fulcrum. Compute the weight of the unknown body and compare with the result of a direct weighing.

(*f*) Slip the knife-edge C to some point O and clamp. Slip a known weight, say 200 g., along between O and B until the beam rests horizontally when placed in the support. Then by applying the principle of moments find the weight of the beam on the assumption that the whole effect of the earth's attraction on the beam is equivalent to one single force equal to the whole weight of the beam and applied at the first position of the knife-edge, i.e. at C, the center of gravity of the beam.

If W represents the weight of the beam, the principle of moments then gives:

$W \times$ distance $CO =$ known weight $\times$ its distance from O.

Compare the result with a direct weighing of the beam.

Tabulate as follows:

(*a*) W_1 =——; its lever arm =——; its moment =——
W_2 =——; its lever arm =——; its moment =——}; per cent of error=——.

(*b*) W_1 =——; its lever arm =——; its moment =——
W_2 =——; its lever arm =——; its moment =——}; per cent of error=——.

(*c*) W_1 =——; its lever arm =——; its moment =——
W_2 =——; its lever arm =——; its moment =——}; sum =——.
W_3 =——; its lever arm =——; its moment =——; {per cent of error=——.

(*d*) W =——; its lever arm =——; its moment =——.
l =——; $\therefore X$ =——; by direct weighing X =——.

(e) W_3 =——; its lever arm =——; its moment =——; W_4 =——; its lever arm =——; its moment =——; sum =——.
W_1 =——; its lever arm =——; its moment =——.
l =——; $\therefore X$ =——; by direct weighing X =——.
(f) Reading of knife-edge at C =——; reading at O =——.
$\therefore$ Lever arm OC =——; known weight =——; its lever arm =——.
$\therefore$ Weight of bar =——; by direct weighing =——; per cent of error =——.

State what general conclusion you are able to draw from (a), (b), and (c). State what method the experiments have shown you for finding the weight of any body without the aid of a pair of scales. Where does the result of (f) show that the total weight of a body, i.e. the sum of the forces of gravity which act upon its particles, may be considered as concentrated?

EXPERIMENT 16

THE PRINCIPLE OF WORK IN THE CASE OF THE INCLINED PLANE

Since the work which a force accomplishes is equal to the product of the force by the distance through which it moves the point upon which it acts, the work done by a force F (Fig. 28) in moving a mass a distance l ($= on$) up the inclined plane on is equal to Fl. But the work done against gravity is equal to the product of the weight W which is moved times the vertical height h ($= mn$) through which W has been raised.

The object of this experiment is to find what relation exists between the work Fl of the acting force and the work Wh of the resisting force, in case there is no friction.

Set the inclined plane of Fig. 28 at an angle of about 45°; hang a convenient weight, say 200 g., at F, and by means of nails or shot adjust the weight of the carriage and contents till it remains in place on the table.

Add nails or shot to the carriage until with continued slight tapping on the plane the carriage will just move slowly and uniformly *down*.

Remove nails one by one, and lay them aside together, until, with like tapping, the carriage moves uniformly *up*.

Weigh the carriage with contents on the beam balance, and

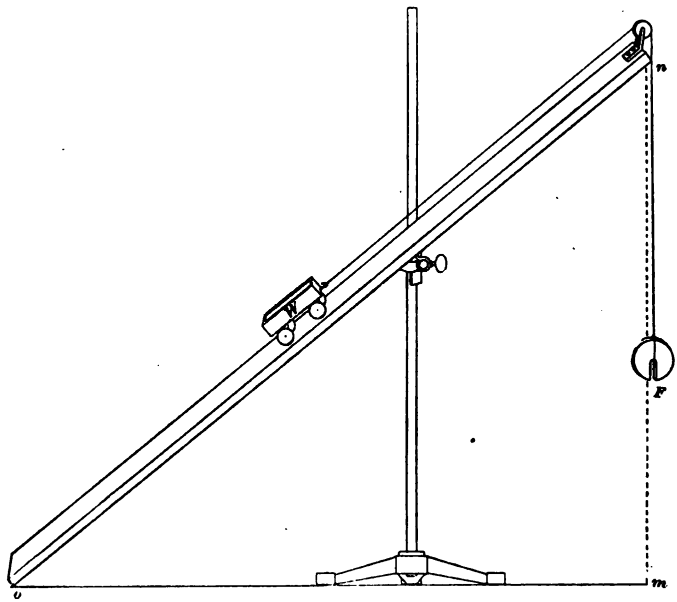


Fig. 28

label the weight "*W* up." Then weigh again after the nails which were laid aside have been added, and label this weight "*W* down."

Measure carefully with a meter stick the height of the plane *mn*, and label it *h*. Similarly, measure the length of the plane *on* and label it *l*.

Take the mean of "*W* up" and "*W* down" as the weight *W* which the force *F* would support on the plane if there were no friction.

Change the angle which *on* makes with the horizontal to about 30° and repeat all observations.

Tabulate as follows:

Trial	*F*	*W up*	*W down*	*W*	*h*	*l*	*Fl*	*Wh*	*Difference*
1	——	——	——	——	——	——	——	——	——
2	——	——	——	——	——	——	——	——	——

State in words the law shown above to exist between the weight on a plane and the force which must act parallel to the plane to keep it in place.

If the board *on* were gradually tipped up so that *h* became larger and larger, would *W*, the weight which could be supported by a given force *F*, vary *directly* or *inversely* with *h*? What sort of curve is the graphic representation of this relation?

EXPERIMENT 17

THE LAWS OF THE PENDULUM

I. To find whether or not the time of swing is different for different amplitudes and different weights. Attach with sealing wax a small weight, preferably a steel ball about 3/4 in. in diameter, to a fine thread about 180 cm. long, and suspend it in a wooden clamp with square jaws, like that shown in Fig. 29.

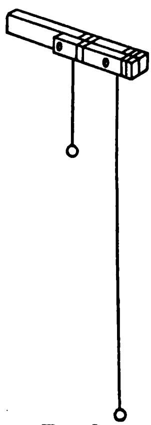


FIG. 29

Let one student set his eye in some particular position, such that the thread is in line with some fixed mark or small object. Then let the pendulum be set into vibration through an arc 10 cm. or 12 cm. long. Let a second student keep his eye on the second hand of a watch while the first taps with his pencil upon the table at the instant of each passage of the pendulum past the fixed mark. When the timekeeper is ready let him call "now" at the instant

of some tap, and record the hour, minute, and second at which he called it, and let the other observer take up the count "one" at the instant of the next tap, and continue up to 100. Let the timekeeper record again the hour, minute, second, and, if possible, the fraction of a second, at which the count 100 occurs.

Increase the amplitude of swing from 20 cm. to 30 cm. and again observe the time of one hundred vibrations exactly as before. Make another trial when the amplitude has been increased to 2 m. or more.

Suspend another pendulum of the same length from support to center of bob, but of quite different mass and material; for example, use for the bob a lead bullet, and see whether one pendulum gains at all upon the other when they are set going together through an arc of 30 cm. or 40 cm.

Tabulate your results as follows:

Arc 10 cm.	*Time of beginning count*	*Time of ending count*	*Total time*	*Time of one vibration*
First trial	$10^h\ 45^m\ 10.4^s$	$10^h\ 47^m\ 25.0^s$	134.6^s	1.346^s
Second trial	10 49 15.0	10 51 29.4	134.4	1.344
Third trial	10 53 47.2	10 56 2.0	134.8	1.348
			Mean =	——
Arc 30 cm.				
First trial	——	——	——	——
Second trial	——	——	——	——
			Mean =	——
Arc 200 cm.				
First trial	——	——	——	——

So long as the amplitude is small, do you find that the period depends upon it at all? What is the effect of a very large amplitude? What influence has the weight of the bob upon the period of a pendulum?

II. To find the relation between the lengths of two pendulums and their periods. Replace the last pendulum by a second one which has a bob like the first, and adjust its length by slipping

it through the clamp, the screw being only moderately tight, until it makes exactly two swings to every one made by the pendulum 180 cm. long. In order to make this adjustment, let one student tap the floor at the instant of each passage of the long pendulum through its middle position, while another does the same with the short one. Adjust until the taps coincide.

Measure the lengths of the two pendulums from the bottom of the clamp to the top of the ball, and add to each measurement the radius of the ball. From these results predict, if you can, how long a pendulum must be made to vibrate three times as fast as the 180-cm. pendulum. Test your conclusions experimentally. Record thus:

Length of pendulum No. 1 = ——
Length of pendulum No. 2 = ——
Length of pendulum No. 3 = ——

$$\frac{\text{Length No. 1}}{\text{Length No. 2}} = \text{——} \qquad \left(\frac{\text{Period No. 1}}{\text{Period No. 2}}\right)^2 = 4$$

$$\frac{\text{Length No. 1}}{\text{Length No. 3}} = \text{——} \qquad \left(\frac{\text{Period No. 1}}{\text{Period No. 3}}\right)^2 = 9$$

III. To find from the above data the length of the second pendulum. Take a mean of all the above observations with shorter arcs on the time of one vibration of the longest pendulum. From this mean and the measured length of this pendulum compute, with the aid of the law just found connecting lengths and periods, the length of a pendulum which will beat seconds.

In order to obtain this quantity as accurately as possible, determine it again from the above data by the graphical method as follows. Let t_1, t_2, t_3 be the respective periods of the three pendulums, and l_1, l_2, l_3 the corresponding lengths. Thus, in the example given above,

$t_1 = 1.346$ sec.	$t_2 = \frac{1}{2} \times 1.346 = .673$ sec.	$t_3 = \frac{1}{3} \times 1.346 = .4487$ sec.
$t_1^2 = 1.812$ sec.	$t_2^2 = .4530$ sec.	$t_3^2 = .2013$ sec.
$l_1 = 180.00$ cm.	$l_2 = 45.00$ cm.	$l_3 = 20.00$ cm.

Now plot t_1^2, t_2^2, t_3^2 as distances to the right of OY (Fig. 30), and l_1, l_2, l_3 as distances above OX, using a scale large enough to make the figure cover a full page and thus obtain three points 1, 2, 3. With a pencil having a very fine point draw the straight line through O, which passes as near as possible to all of the points 1, 2, 3. Read off upon this straight line the length

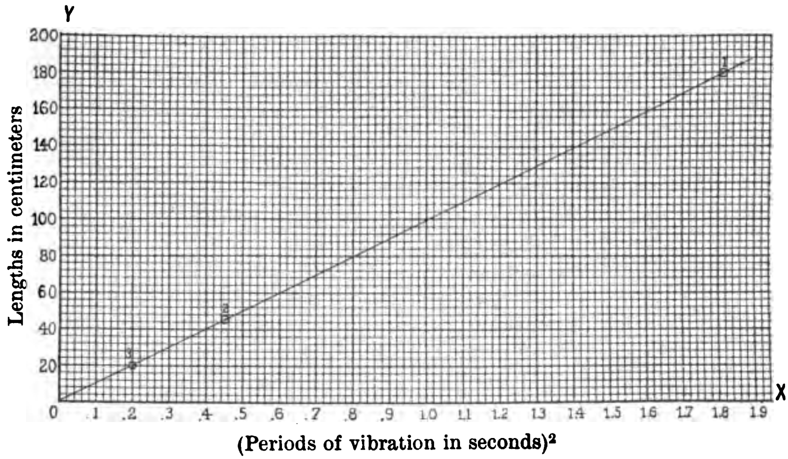


FIG. 30

l corresponding to the value $t^2 = 1$. This is the length of the seconds pendulum.

This graphical method here outlined is often the simplest and most satisfactory way of averaging a number of observations.

State in your own words the laws of the pendulum which have been proved by the above experiments.

How would you obtain from the graph the time of a pendulum of any assigned length, say 141 cm.?

It is shown in more advanced work in physics that the velocity g which a falling body acquires in a second can be found by multiplying the length of the seconds pendulum by π^2. Compute g in this way and compare with the accepted value, viz. 980.

EXPERIMENT 18

THE LAW OF MIXTURES AND THE WATER EQUIVALENT OF A METAL VESSEL

I. The law of mixtures. The unit of heat is called the *calorie*. It is defined as the amount of heat which passes into 1 g. of water when its temperature rises 1° C., or the amount which passes out of 1 g. of water when its temperature falls 1° C. Thus, when the temperature of 100 g. of water rises 10° C., we say that $100 \times 10 = 1000$ calories of heat have entered the water; or when the temperature of 100 g. of water falls 5° C., we say that 500 calories of heat have passed out of the water.

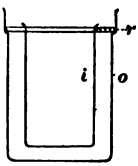


FIG. 31

Allow a dry thermometer to stand for two or three minutes in a metal vessel of at least 300 cc. capacity,—for example, the inner vessel *i* of the *calorimeter* of Fig. 31, and then take its reading and call this the temperature of the room.

(*a*) From a vessel of cold water pour 100 g. of water into each of two small vessels,—for example, the small brass cylinders used in Experiment 3. By heating with a Bunsen flame and by continual stirring adjust the temperatures of the two vessels of water until one is 6° or 8° below the temperature of the room as measured by one thermometer, while the other is about the same amount above it as measured by a second thermometer. Immediately after taking these temperatures pour the two bodies of water together into the vessel which is at the temperature of the room. Stir for about one minute with both thermometers, then take the temperature of the mixture on each thermometer.[1]

[1] Use two thermometers because the temperature of one vessel would otherwise change while that of the other was being taken. Take the final temperature with both thermometers because the readings of inexpensive thermometers often differ from one another as much as ½° C.

Compute and record how many calories of heat the warmer water has lost and how many the colder water has gained.

(*b*) Repeat, this time mixing 200 g. at a temperature about 6° C. below that of the room with 100 g. at a temperature 12° C. above that of the room. Record thus:

(*a*)

Temperature of room	= 19.15° C.
Temperature of first 100 g. water	= 12.7° C.
Temperature of second 100 g. water	= 25.7° C.
Final temperature of mixture on first thermometer	= 19.1° C.
Final temperature of mixture on second thermometer	= 19.3° C.
Number of calories gained by first 100 g.	= ——
Number of calories lost by second 100 g.	= ——

(*b*)

Temperature of 200 g. water	= ——° C.
Temperature of 100 g. water	= ——° C.
Final temperature of mixture on first thermometer	= ——° C.
Final temperature of mixture on second thermometer	= ——° C.
Number of calories gained by the 200 g.	= ——
Number of calories lost by the 100 g.	= ——

State in your notebook the relation which you find to hold in the above experiments between the number of calories gained by the body whose temperature rises and the number lost by the body whose temperature falls, remembering, of course, that your temperature readings may easily be in error as much at .1°. This is found to be a law which governs the process of heat exchange in all cases of mixture of bodies at different temperatures.

In the above experiments the vessel into which the water was finally poured was in every case at the temperature of the room. The next experiment is one in which this is not the case.

II. Water equivalent of a metal vessel. Pour 150 g. of water into the inner vessel *i* (Fig. 31) of the calorimeter[1] and 100 g.

[1] If a calorimeter is not available, use two of the small cylinders of Experiment 3, but in this case put 75 g. of water into each and make the temperature of one about as far above the temperature of the room as that of the other is below it.

into one of the small cylinders used in Experiment 3. Adjust the temperature of the 150 g. until it is about 10° below that of the room, while the temperature of the 100 g. is made a little more than one and a half times as much above that of the room. Place the inner vessel of the calorimeter in the outer one *o* (Fig. 31), supporting it by the ring *r*. This is done to avoid communicating heat to the water from the hand. With different thermometers, stir the water in each vessel thoroughly, and at the same time tip the vessel containing the cold water so as to bring the water into contact with as much of the walls as possible. This is to give the whole of the vessel the temperature of the water. Read the temperature of the water in each vessel very accurately, then quickly pour the warmer water into the colder. Stir for half a minute, then read the final temperature on each thermometer. Compute the number of calories lost by the hot water and the number gained by the cold. They are no longer equal. Why? From the difference and the number of degrees through which the vessel has been raised, find the number of calories required to raise it through 1° C. This is called the *water equivalent of the calorimeter*, since it is the number of grams of water to which the vessel is thermally equivalent. The following are typical observations.

Temperature of the 150 g.	=	8.1° C.
Temperature of the 100 g.	=	38.0° C.
Temperature of mixture	=	19.5° C.
Rise in temperature of vessel	=	11.4° C.
Calories gained by cold water	=	1710
Calories lost by hot water	=	1850
Difference (= calories going to vessel)	=	140
Water equivalent of vessel	=	12.3

The calculated value of the water equivalent of a brass vessel is its weight (in this case 135 g.) times the specific heat of brass (viz. .095; see Experiment 19). This product is in this case equal to 12.8, and differs from the observed value, 12.3, by 4 per cent.

The only reason for making the initial temperature of the 100 g. one and a half times as far above the temperature of the room as that of the 150 g. was below it was to make the final temperature of the mixture the same as that of the room. Can you see why this arrangement is desirable if we wish to know the temperature of the mixture accurately?

Why did we not need to consider the heat absorbed by the vessel into which we poured the two bodies of water in the experiments on the law of mixtures?

If you read one of the thermometers which gave you the final temperature of the mixture .1° too high, what is the real value of the water equivalent? (Actually work it out, making the final temperature .1° higher.) Do you then consider that your result is within the limits of legitimate observational error?

EXPERIMENT 19

SPECIFIC HEAT

I. Relative amounts of heat given up by equal weights of lead, iron, and aluminum in falling 1° C.[1] Let the tops be unscrewed from three steam boilers such as those shown in Fig. 36, and let each boiler be filled with enough water to stand say half an inch high in the gauge shown on the right. Let Bunsen burners be lighted under each; then let one student weigh out 150 g. of lead shot, place it in the dipper *d* (Fig. 32), and set the latter inside the boiler. Let another do the same with 150 g. of small iron nails, and a third with 150 g. of aluminum punchings. Let each weigh or measure out 150 g. of water, place

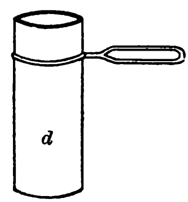


FIG. 32

[1] It is intended that either three or six students work together on this experiment, according as the class has been working singly or in groups of two.

it in one of the cylinders used in Experiment 3, and bring it to the temperature of the room. Let each student take and record the temperature of the water in each of the three cylinders.

After the water has been boiling for about five minutes in each boiler, let each student quickly pour the contents of his dipper into the water in his cylinder; then let him stir the mixture for at least half a minute and take the final temperature in each of the three vessels. (At this point let each student, in preparation for II, fill his dipper with dry shot until dipper and shot weigh between 800 g. and 900 g.; then let him take the weight exactly, place in the boiler, and sink his thermometer in the shot so that the bulb is well down toward the bottom.) Since, in the above experiment, equal weights of the three metals have been raised to the same temperature and then plunged into equal quantities of water at the same temperature, if the final temperatures are different, what conclusion must you draw regarding the capacities for giving out heat which equal weights of different bodies have per degree fall in their temperatures?

The number of calories of heat required to raise the temperature of 1 g. of a substance 1° C., or the number of calories given out by 1 g. in cooling 1° C., is called the specific heat of the substance.

Record in your notebook what, in a general way, your experiment shows about the relative specific heats of different metals, and about how many times it shows the specific heat of aluminum to be greater than that of iron, and that of iron to be greater than that of lead. (These specific heats must be approximately proportional to the three temperature changes, since each metal has fallen through approximately the same number of degrees, i.e. from about 100° to about the temperature of the room.)

II. Accurate determination of the specific heat of lead. Weigh the inner vessel *i* of the calorimeter of Fig. 31; then prepare some water whose temperature is about 12° C. below that of

the room. Pour about 200 g. of it into the calorimeter. Weigh again, and replace the calorimeter in its jacket *o* (Fig. 31).[1]

With a glass rod or a pencil stir the shot in the dipper, and after it has been heating for fifteen minutes or more record the temperature indicated by the thermometer immersed in it.

Transfer the thermometer to the cold water in the calorimeter and stir thoroughly. When its temperature reaches some convenient point, which should not be less than 8° C. below the temperature of the room, quickly pour the shot from the dipper into the water. (If dew has collected on the outside of the inner vessel, wipe it all off just before mixing.)

Stir the mixture for about two minutes, then take the final temperature. Weigh the dipper, then tabulate results as follows:

Weight of dipper + shot	= 1201 g.
Weight of dipper alone	= 103 g.
∴ Weight of shot alone	= 1098 g.
Weight of calorimeter	= 157 g.
Weight of calorimeter + water	= 415.9 g.
∴ Weight of water alone	= 258.9 g.
Temperature of room	= 22° C.
Temperature of shot	= 98.5° C.
Initial temperature of water	= 12.8° C.
Final temperature of mixture	= 22.3° C.
Rise in temperature of water	= 9.5° C.
Water equivalent of calorimeter, from Experiment 18	= 14.7 g.
Weight of water + water equivalent	= 273.6 g.
Number of calories absorbed by water + calorimeter	= 2599
Fall in temperature of shot	= 76.2° C.
∴ Heat given up by shot per gram per 1° C. = specific heat of lead	= .0311
Accepted value	= .0315
Per cent of error	= 1.3

[1] If the laboratory is not equipped with calorimeters, use instead the cylinder of Part I without any jacket. In this case make the weights of water in the cylinder and of lead in the dipper one half of the above amounts.

State in your notebook what you understand to be represented by the quantity which you have found.[1]

When the shot and the water were mixed the changes in the temperature of each took place very rapidly at first, but very slowly as the temperature of each approached the final value. Can you see a reason, therefore, why it was advisable to choose the conditions so that the final temperature should be close to the temperature of the room? Remember in your answer that it was necessary to wait two or three minutes for the mixture to reach its final temperature, and that a body which is hotter than the room is always losing heat to the room, while one which is colder than the room is always gaining heat from it. It is these losses of heat by radiation which constitute the greatest difficulty in the way of accurate measurements by the method of mixtures.

[1] A further very interesting experiment which may be inserted for the benefit of those who have time and inclination for extra work is the following.

To find the temperature of a white-hot body. By means of a thin copper wire suspend from a support placed from 50 cm. to 100 cm. above the table a piece of copper rod about 2 cm. long and 12 mm. in diameter. Adjust the length of the suspension so that the copper hangs in the hottest part of a Bunsen flame (just above the inner cone).

Weigh a calorimeter of 300 cc. capacity; then fill it about half full of water whose temperature has been reduced 12° or 15° below that of the room, and weigh again. Then replace it in its jacket.

After the copper has been heating for about ten minutes take the temperature of the water very carefully (it should now be from 8° to 10° below the temperature of the room); then, all in the same second, remove the flame and lift the calorimeter so as to bring the white-hot copper to the bottom of the vessel of water.

Stir the water thoroughly for one or two minutes; then take the final temperature.

Weigh the copper rod and with it as much of the copper wire as was immersed.

Assuming that .095 calories (the specific heat of copper) came out of each gram of copper for each degree of fall in its temperature, calculate what was the temperature of the white-hot copper.

Duplicate conditions as nearly as possible and see how closely two observations will agree.

Why was it unnecessary to attempt to weigh the shot to tenths of a gram?

After the experiment spread out the shot in a thin layer on a cloth to dry.

EXPERIMENT 20

THE MECHANICAL EQUIVALENT OF HEAT

The object of this experiment is to show that when a falling body strikes the earth the kinetic energy of the moving mass is transformed into the energy of molecular vibrations, i.e. into heat, and to find how many gram meters of mechanical energy must disappear in order to produce 1 calorie of heat. This quantity is called the "mechanical equivalent of heat." It is obtained by finding the rise in the temperature of shot when it falls through a known height.

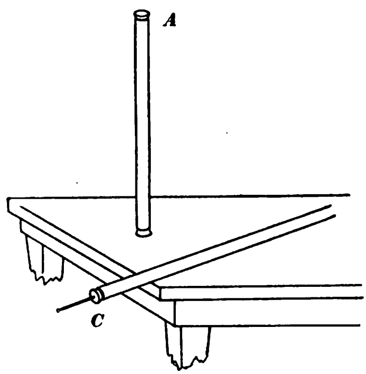


FIG. 33

Pour about 2 kg. of dry shot into a metal vessel and set it in a cool place, e.g. in a bath of ice water, until its temperature is 5° or 6° below that of the room.

Pour this shot into a paper tube (Fig. 33) about a meter long and 5 cm. or 6 cm. in diameter, made by rolling up a large number of turns of heavy brown paper and then securing them with glue and string. The tube should be closed with two tightly fitting corks.

Mix the shot very thoroughly by shaking the tube, and by slowly inclining it so that the shot will run from end to end.

In so doing, however, grasp the tube near the middle rather than at the ends, for it is desirable that the temperature of the ends be not influenced by the heat of the hands.

After inverting in this way from five to ten times, remove the upper cork *A* and insert cork *C* (Fig. 33), through which passes a thermometer; then gradually incline the tube until all the shot has run down to the thermometer end and there completely surrounds the bulb.

Holding the tube inclined as in the figure, twist the thermometer about in the shot for about two minutes, and then take the temperature. If this is more than 2° or 3° below the temperature of the room, continue the shaking and rolling of the shot from one end to the other until its temperature has risen to within about 3° C. of that of the room.

Record this temperature, quickly replace cork *C* by cork *A*, hold the tube upright as in the figure, and turn it completely over say seventy times in rapid succession, placing the lower end on the table at each reversal, so that the falling shot may not force out the corks. At each reversal the potential energy acquired by the shot in being lifted the length of the tube is converted into kinetic energy in the descent, and this kinetic energy is all transformed into heat energy at the bottom. On account of the poor conductivity of the cork and paper practically all of this heat goes into the shot, and but an insignificant portion of it into the corks and tube.

After the seventy reversals very quickly replace cork *A* by cork *C*, and take as before the final temperature of the shot.

Remove cork *C*, set the tube on end, and measure the distance from the top of the shot to the position which was occupied by the bottom of cork *A*. This is the mean height through which the shot has fallen at each reversal.

The total quantity of work which has been transformed into heat is the weight W of the shot $\times$ the height h of fall

(expressed in meters) × 70. The number of calories of heat developed is the weight of the shot W × its specific heat (.0315) × the rise in temperature (t_2-t_1). Hence, if J represent the number of gram meters of energy in a calorie, we have

$$J \cdot W \times (t_2 - t_1) \times .0315 = 70 \cdot W \cdot h.$$

$$\therefore J = \frac{70\,h}{(t_2 - t_1)\,.0315}.$$

It will be noticed that the weight W of the shot cancels out; hence it need not be taken.

In the above directions the attempt is made to eliminate radiation and conduction losses by making the initial temperature of the shot about as far below the temperature of the room as the final temperature is to be above it. This is the usual way of eliminating radiation, when, as in this case, the change in temperature between the readings of the initial and final temperatures takes place rapidly and at a uniform rate.

Repeat the experiment several times if time permits. Record the results thus:

	First trial	*Second trial*	*Third trial*	
Temperature of room	= 18.5° C.	18.5° C.	18.5° C.	Mean value
Initial temperature	= 16.0° C.	17.1° C.	16.7° C.	= 437 g. m.
Final temperature	= 21.7° C.	22.6° C.	21.0° C.	Accepted value
Number of reversals	= 100	100	80	= 427 g. m.
Height of fall (h)	= .76 m.	.76 m.	.76 m.	
Mechanical equivalent	= 423 g. m.	439 g. m.	449 g. m.	% of error = 2.4

What conclusions do you draw from your experiment?

The chief source of error in the experiment arises from the fact that the thermometer requires considerable time to come to the temperature of the shot. During all this time the shot is gaining or losing heat by conduction and radiation, so that the temperature indicated may not be quite the mean temperature of the shot. This source of error is unavoidable.

Why did we attempt to have the initial temperature as far below the temperature of the room as the final temperature was above it?

EXPERIMENT 21

COOLING THROUGH CHANGE OF STATE

I. Solidification a heat-evolving process. The object of this experiment is to show that just as it requires an expenditure of heat energy to melt ice or any other crystalline substance, so when water or any liquid freezes, i.e. changes back to the crystalline form, heat energy is given up to the surroundings.

Support vertically in a burette holder or other clamp a test tube in which has been placed enough loose crystals of acetamide to fill it about a third full. Then heat gently with a Bunsen burner until the crystals are all melted.[1] Slowly insert a thermometer into the liquid, but watch the thread all the time, and if it rises to within half an inch of the top of the bore, instantly remove the bulb from the liquid. *The thermometer will burst under the force of expansion of the mercury if the thread reaches the top of the bore.* If there is an expansion chamber at the top, this danger is of course avoided. If there is no expansion chamber, it will be safer to melt the acetamide by dipping the tube into boiling water rather than by applying the flame directly.

As soon as the liquid acetamide has cooled down to about 100° C., insert the thermometer in it permanently, and without touching further either the tube or the thermometer, watch carefully both the liquid and the thread of mercury as cooling takes place. The temperature may fall as low as 60° C. before crystallization begins. As soon as crystals begin to form, what sort of a temperature change do you observe? What conclusion do you draw from this observation? Watch the temperature for

[1] If the acetamide has absorbed much moisture, boil it.

two or three more minutes and decide whether or not the temperature of a solidifying liquid remains constant during the process of solidification. Since it is giving up heat rapidly all this time, it must get it from some source. What must this source be?

II. The curve of cooling. Again raise the temperature to 100°C, taking the precautions mentioned above against breaking the thermometer. Record the temperature every half minute as the

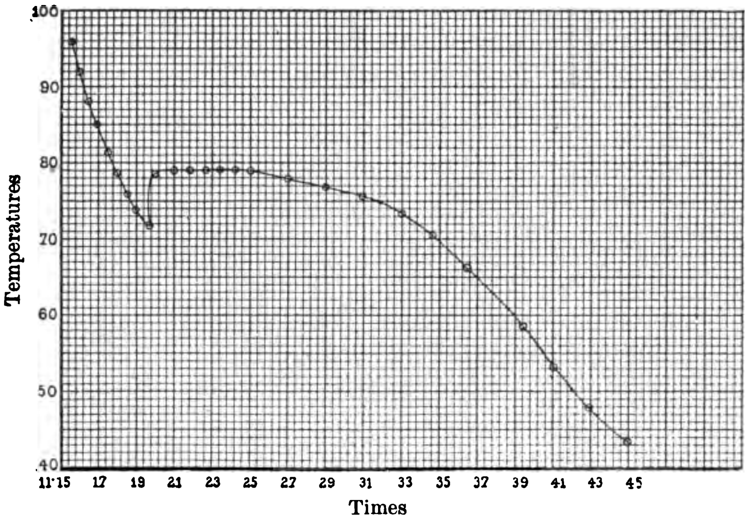


FIG. 34

substance cools from about 100° C. to 45° C. Plot these observations in the manner shown in Fig. 34, temperatures being represented by vertical distances and times by horizontal distances. Thus the observations plotted in the figure began at 11:15 A.M. and continued to 11:45 A.M. The curve shows that between 11:15 and 11:19.5 the temperature fell rapidly from 100° to 71.8°, that it then rose suddenly to 79°, remained there five minutes, then fell slowly during the next twenty minutes from 79° to 43.5°.

Write in your notebook a similar explanation of your own curve. Almost any substance, if kept very quiet and cooled through its freezing point, will show the phenomenon of *undercooling* exhibited here by the acetamide, i.e. its temperatures will fall a little below the freezing points before the crystallization gets started. It will then rise suddenly to the freezing point and remain there until the crystallization is practically complete.

If time permits, dip a test tube containing a little distilled water into a freezing mixture of salt water and ice, the temperature of which is say $-8°$ C., and see if water too will not show the same behavior. (The tube must be kept very quiet.) If you get the temperature down to $-2°$ or $-3°$, lift the test tube, stir, and observe the instant formation of the crystals of ice. If you wish to try a substance which does not undercool, treat a little naphthaline [1] precisely as you treated the acetamide.

EXPERIMENT 22

THE HEAT OF FUSION OF ICE

The heat of fusion of ice, i.e. the number of calories of heat required to change a gram of ice at 0° C. into water at 0° C., or the number given up when a gram of water changes to ice, may be determined experimentally as follows.

Weigh the inner vessel of a calorimeter of about 300 cc. capacity first when empty, and then after it has been filled about two thirds full of water.[2]

Heat this water to a temperature of about 25° C. above that of the room; then replace the inner vessel in its jacket (Fig. 31).

[1] Naphthaline can be obtained at any drug store. Acetamide will have to be purchased at a chemical supply house.

[2] If you use the small cylinders of Experiment 3 for the calorimeters, take just half of the amounts of ice and water indicated.

Prepare a lump of clear ice of about the size of a hen's egg, and perform the following operations in quick succession.

While one student is drying the ice upon a towel let another stir the water in the calorimeter thoroughly. If its temperature is less than 15° C. above that of the room, heat it up again until it is between 15° C. and 25° C. above. Again check the weight, for the loss by evaporation may not have been inappreciable. Stir vigorously; then quickly take a careful reading of the temperature, keeping the thermometer bulb all the time immersed, and not more than a second or two after the reading let the first student drop the dry ice into the water, being very careful not to spill a drop. The splash may often be avoided by letting the ice slide along the thermometer into the water.

Stir continuously while the ice is melting and read the temperature of the water just after the ice has all disappeared. This temperature should be from 2° C. to 10° C. below the temperature of the room. If it should happen to be above the room temperature, try again with a slightly larger piece of ice. The limits here given are chosen so as to make it legitimate to assume that the heat exchanges which take place between the calorimeter and the room are, on the whole, negligible.

Again weigh the inner vessel of the calorimeter, with its contained water, and take the difference between this weighing and the last as the weight of the ice.

Let x represent the heat of fusion of ice and w the weight in grams of the ice melted. Then the number of calories expended in melting the ice is wx. After the ice is melted it becomes w grams of water at 0° C. This water is then raised to the final temperature t of the mixture. The number of calories required for this operation is wt. All of this heat has come from the cooling of the water and the calorimeter. If the weight of the water cooled is W and its initial temperature t_1, while the water equivalent of the calorimeter is e, then the

total number of calories given up by the water and calorimeter is $(W+e)(t_1-t)$. Hence, by equating "heat lost" and "heat gained," it is easy to obtain x, the only unknown quantity of the equation. Tabulate as follows :

Weight of calorimeter	= ——
Weight of calorimeter + water	= ——
∴ Weight of water	= ——
Temperature of room	= ——
Initial temperature of water	= ——
Final temperature of water	= ——
∴ Fall in temperature of water	= ——
Weight of calorimeter + water + ice	= ——
∴ Weight of ice	= ——
Water equivalent of calorimeter (Experiment 18)	= ——
∴ Heat of fusion of ice	= ——
Accepted value is 80.	
∴ Per cent of error	= ——

State in your notebook the meaning of the "latent heat of water," the quantity which has been found above.[1]

EXPERIMENT 23

THE BOILING POINT OF ALCOHOL

The boiling point of a liquid is defined as the temperature at which the pressure of its saturated vapor becomes equal to the atmospheric pressure. There are, therefore, two ways in which the boiling point of alcohol may be obtained, and these

[1] A further experiment on latent heat, which may be introduced for the benefit of those who have time and inclination for extra work, is the following.

To find the heat of condensation of steam. Pass dry steam into say 250 g. of cold water, the temperature of which is 10° C. below that of the room, until the temperature is 10° above that of the room. Weigh again to find the weight of the steam, and then calculate as above how many calories of heat have been given up by each gram of steam in condensing.

two ways should give identical results. The first is to confine the liquid and its vapor alone in a closed vessel, and then to measure the pressure exerted by the vapor at different temperatures. That temperature at which the pressure becomes equal to atmospheric pressure will then be the boiling temperature. The second and more direct way consists in simply boiling the liquid in an open vessel and observing the temperature indicated by a thermometer held in the vapor rising from the liquid.

I. Temperature at which pressure of saturated vapor becomes equal to atmospheric pressure. A glass tube *A* (Fig. 35) is closed at one end, and is then bent into the U-shape and partially filled with mercury. Some alcohol is then poured in, which by careful tilting is worked around into the closed arm, while the air is altogether worked out of this arm. With this arrangement proceed as follows.

FIG. 35

Immerse the tube and a thermometer together in a vessel of water, and, keeping the short arm completely immersed, heat slowly, stirring continually. As the temperature increases a point is reached at which alcohol vapor begins to form in the closed tube. Still further increase in temperature causes the mercury to sink farther and farther in the closed end. When the levels of the mercury in the two arms are the same, it is clear that the pressure of the alcohol vapor is just equal to the atmospheric pressure.

Raise the temperature of the water gradually and stir thoroughly until this condition is reached; then read and record the temperature.

Continue heating until the level in the short arm is 5 cm. lower than that in the long one. Then again read the thermometer and compute how much the boiling point of alcohol increases per centimeter increase in the barometric pressure.

II. Temperature of vapor rising from boiling liquid. Place a little alcohol in a large test tube; put a few tacks in the bottom

of the tube in order to assure smooth boiling; then immerse the lower end of the tube in a vessel of water and heat the water until the alcohol boils vigorously. Hold the bulb of a thermometer in the tube a little distance above the surface of the boiling liquid. As soon as the thermometer reading becomes stationary, take the temperature and compare with that obtained in I. Record thus:

I. Temperature at which alcohol vapor exerts pressure of 1 atmosphere = ——° C.
   Temperature at which alcohol vapor exerts pressure of 1 atmosphere + 5 cm. of mercury = ——° C.
   Rise in boiling point of alcohol per cm. increase in pressure = ——° C.
II. Temperature of vapor rising from boiling alcohol = ——° C.
   Difference between results of I and II = ——.

State in your notebook what you consider to have been proved in this experiment.

EXPERIMENT 24

TO TEST THE FIXED POINTS OF A THERMOMETER, AND TO FIND THE CHANGE IN THE BOILING POINT OF WATER PER CENTIMETER CHANGE IN THE BAROMETRIC PRESSURE

Fill the boiler of Fig. 36 half full of water, and thrust the thermometer through a tightly fitting cork in the top until the 100° point is only 2 mm. or 3 mm. above the cork.

Attach an open-arm manometer *u* (Fig. 36) to the exit *o*, and then boil, regulating the flame until the mercury stands at the same height in both arms of the manometer.

After the water has been boiling steadily for two or three minutes, read the thermometer *very carefully*. Then take the barometer reading. Next place a piece of tightly fitting rubber tubing over the escape tube *e* and partly close the free end of it with a pinchcock until the difference in the levels in the

manometer arms, due to the partial closing of the vent for the steam, amounts to 2 cm. or 3 cm. Read the thermometer and (with a meter stick) the difference in the levels in the manometer arms.

Close the pinchcock still further, until the difference in level amounts to 4 cm. or 5 cm.; then read again.

Continue thus, taking readings at intervals of about 2 cm., until the difference in level amounts to 8 cm. or 10 cm. It may be necessary to use several burners in order to obtain the last readings, for the steam must be generated very rapidly in order to compensate for the inevitable leakage.

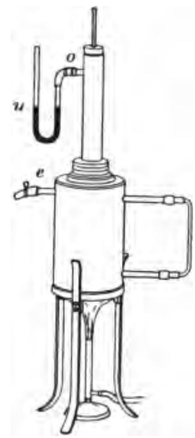


FIG. 36

From each of these readings calculate the changes produced in the boiling point by a change of 1 mm. in the barometric height. Take a mean of all these calculations as the correct value of this quantity.

From this result and the barometer reading calculate what your thermometer would read under a pressure of 76 cm. The error in the graduation of the thermometer is the difference between this result and 100.

Test the zero point of the same thermometer by sinking it up to the zero mark in a funnel filled with melting snow or finely chopped ice over which a little water has been poured, and allowing it to remain there until the thread is stationary. Tabulate results thus:

	First	*Second*	*Third*
Difference in levels in gauge	= ——	——	——
Corresponding boiling-point readings	= ——	——	——
Change in boiling point per millimeter	= ——	——	——
Mean change per millimeter	= ——	Barometer height	= ——
∴ Reading of thermometer at 76 cm.	= ——	Error	= ——
∴ Reading of thermometer at 0° cm.	= ——	Error	= ——

State in your own words the conclusion which you draw from this experiment regarding the effect of pressure upon the boiling point.

EXPERIMENT 25

MAGNETIC FIELDS

I. The magnetic field about a bar magnet. (*a*) Lay a bar magnet in a groove in a board (Fig. 37). Pin a sheet of blueprint paper over the magnet; from a sifter containing iron filings sift the filings evenly, but not too thickly, over the paper from a height of a foot or two. Tap the paper gently with a pencil. The filings will be found to have arranged themselves in lines running in symmetrical curves from one pole around to the other.

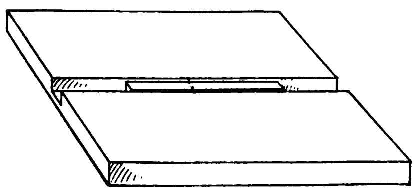


FIG. 37

(*b*) Hold a short compass needle in a number of positions over the board, and observe whether or not there is any connection between the direction of the curved lines and the direction taken by the needle. These lines simply indicate the direction of the magnetic force. They are called *magnetic lines of force.*

(*c*) Carefully place the board in strong sunlight without jarring the filings, and wait until the uncovered parts of the paper have turned brown. Return the filings to the box and put the blueprint paper to soak in water for about five minutes. Place the paper flat against a pane of glass to dry, and when it is dry fasten it in your notebook.

If blueprint paper is not provided, or if the sun is not bright enough to make satisfactory prints, simply draw in your notebook a copy of the curves shown by the filings. In these

drawings and also on the blueprints indicate the *N* and *S* poles of the magnets and furnish the lines with arrows pointing in the direction in which an *N* pole tends to move. (An *N* pole is one which, when the magnet is suspended freely, points toward the north.)

II. The magnetic fields about certain combinations of horseshoe magnets. By sprinkling iron filings upon a sheet of card-

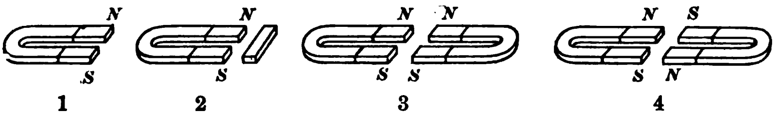


FIG. 38

board or glass placed over various combinations of magnets, as indicated in the accompanying figures (Fig. 38), determine the nature of the magnetic field in each case, and indicate by a drawing in the notebook.

EXPERIMENT 26

MOLECULAR NATURE OF MAGNETISM

I. Making a permanent magnet. Mark one end of a knitting needle with a file for the sake of identification.

(*a*) Stroke it once from end to end with the *N* pole of a horseshoe or bar magnet. Place the needle on the table in the east-and-west line which passes through the middle of a compass needle resting upon the table, and slide the knitting needle up toward the compass until it produces in it a deflection of 10°; then mark the positions of the two ends of the knitting needle on the table. Does the near end of the knitting needle repel or attract the north-seeking end of the compass needle? Is it an *N* or an *S* pole? (If in doubt, suspend the needle in the middle by a thread and wire stirrup and see which end points north.)

(*b*) Reverse the knitting needle so that the second end occupies exactly the position originally occupied by the first. Compare the strengths and signs of the two poles.

(*c*) Stroke the needle once more with the magnet precisely as at first, and again bring it to precisely the same position. Is the deflection increased? How much?

(*d*) Continue to stroke the magnet in the same way until it is saturated, i.e. until further stroking produces no more change in the effect upon the compass.

II. Effect of jars on a saturated magnet. (*a*) Drop the needle on the floor and again test its strength exactly as before. Record the change.

(*b*) Strike the needle a number of sharp blows against the table and test again.

(*c*) If magnetization consists in a particular arrangement of the molecules of the needle, what effect would you expect violent jars like the above to have upon it?

III. Effect of breaking a magnetized needle. (*a*) Magnetize a long darning needle and note which end is N and which S. Then dip the whole needle into a box of iron filings and note whether or not it possesses any appreciable magnetism in the middle.

(*b*) Break it in two and test the two freshly broken ends first by means of the compass and then by means of the iron filings. Test also the old ends.

(*c*) Break one of the halves again if possible and repeat as above.

(*d*) Summarize the results of these experiments and explain the observed effects on the assumption that a magnet consists of rows of molecular magnets arranged end to end.

IV. Effects of heating a magnet. (*a*) Note how much deflection is produced when one of the small magnets, say an inch long, obtained by breaking the darning needle, is placed at a given distance from the compass; then make a stirrup out of copper wire, place the needle in it, heat it to redness in the

Bunsen flame, and again test it by means of the compass. Record the effect.

(*b*) Heat again to redness, and then transfer it quickly to a position between the poles of a horseshoe magnet. Let it remain there until cool and test again with the compass.

(*c*) Explain both of the effects on the assumption that magnetization consists in a particular arrangement of the molecular magnets. (Remember that the molecules of the needle are set into violent agitation when the needle is heated to redness.)

V. Making a magnet by induction. (*a*) Hold a short piece of unmagnetized knitting needle or a small steel nail between the poles of a horseshoe magnet and tap it vigorously with some heavy object without allowing it to touch the magnet. Remove it and test its poles with the compass needle.

(*b*) Turn it end for end, replace it between the poles of the horseshoe magnet, and tap again. Record the change which you observe in its poles.

(*c*) Remove the steel rod from a tripod or take one of the small steel rods used for bending in Experiment 12. Hold it nearly vertical in a north-and-south plane, the upper end being tilted 20° or 30° toward the south. Strike the upper end three or four sharp blows with a hammer and then test the two ends of the rod for magnetism. Note which end is an N pole.

(*d*) Repeat with the ends of the rod reversed. Which end is now an N pole? Explain on the assumption that the molecules are permanent magnets and that magnetization consists in an alignment of these molecules.

From all of the above experiments, what picture do you make to yourself regarding the operations which go on within a bar of iron when it is magnetized? Draw a diagram to represent the probable arrangement of the molecular magnets in a magnetized bar, and another to represent some possible arrangement in an unmagnetized bar.

EXPERIMENT 27

STATIC ELECTRICAL EFFECTS

To make an electroscope bend a piece of No. 18 copper wire into the form shown in Fig. 39, thrust it through a rubber stopper,[1] hang a piece of aluminum foil about 2 in. long over the horizontal part of the wire, and insert in a glass flask as shown.[2]

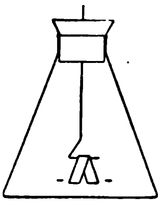


FIG. 39

I. Conductors and nonconductors. (*a*) Attach one of the steel balls of Experiment 3 to a silk thread by means of sealing wax, or simply stick a penny to the end of a glass rod with the aid of sealing wax. Such an arrangement is called a *proof plane*. Charge this proof plane by letting it rub along a stick of sealing wax which has been electrified by being rubbed with flannel; then touch it to the wire of the electroscope. What does the instant divergence of the leaves show regarding the ease with which a charge of electricity passes through this metal wire? What does the fact that the leaves stand apart show regarding the nature of the force which the two parts of the same charge going to the two leaves exert upon each other?

(*b*) Touch the wire of the electroscope for an instant with a piece of sealing wax which has not been electrified. Touch it with a wooden ruler. Touch it with your finger. Which of the three conducts off the charge most readily?

[1] If the rubber stopper has not a hole through it already, you can easily make one with a hot knitting needle. If it already has a hole which is too large, cover the wire with sulphur or sealing wax. This will not only make it fit, but it will also improve the insulation.

[2] An electroscope so made will hold its charge for hours, even in summer. To cut the foil blow it out flat on a sheet of paper, lay another sheet on top of it, leaving one edge uncovered, and then cut off a strip with a sharp knife or razor. A saw stroke will work best.

(*c*) Charge the proof plane or steel ball, again touch it with the finger, and then try to charge the electroscope with it. Explain why the rubbed sealing wax holds its charge when it is held in the hand, while the proof plane or steel ball loses its charge as soon as it is touched with the finger.

II. Positive and negative electricity. (*a*) Charge the electroscope as above, then bring the charged sealing wax toward it. Record the effect produced on the divergence of the leaves. Explain this effect in view of the fact that the charge on the wire of the electroscope is a part of the charge which was originally on the sealing wax (see I (*a*)).

(*b*) Rub a glass rod with silk, then bring it slowly toward the charged electroscope. Record the first effect observed. (If you bring the rod too close, the effect will be reversed.) In order to account for this effect, what sort of a force must we now assume the charge on the glass rod to exert upon the charge on the electroscope?

A charge of electricity which acts as does the charge on a glass rod which has been rubbed with silk is arbitrarily called a *positive* (+) charge. A charge which acts like the charge on the sealing wax when it has been rubbed with flannel is called a *negative* (–) charge.

(*c*) Discharge the electroscope, then charge it with the aid of the proof plane and glass rod, precisely as you first charged it with the aid of the proof plane and sealing wax. Note and record the behavior of the leaves when you now bring, first the glass rod, and then the charged sealing wax toward the electroscope. In view of all these observations, state how, in general, *like* and *unlike* charges of electricity act upon one another.

(*d*) Charge the electroscope either positively or negatively; then rub a piece of paper on the coat sleeve and determine by bringing the paper near the electroscope whether it has received

a + or a − charge. Flick your handkerchief across the suspended steel ball and see whether it has received a + or a − charge.

III. To charge two bodies simultaneously by induction. Hold two suspended steel balls in contact. Bring a piece of electrified sealing wax to within an inch of the balls, holding it in the line joining their centers. While it is in this position separate the two balls, then bring each over a negatively charged electroscope. Has the ball which was nearest the sealing wax received a + or a − charge? Record the sign of the charge on the other ball. If an uncharged body contains equal amounts of both positive and negative electricity which, under ordinary circumstances, are so uniformly distributed that they completely neutralize each other, and if one or both of these electricities is free to move through the body under the influence of an outside charge, can you account for the effects which you have observed?

IV. To charge the electroscope by induction. Bring the charged sealing wax near enough to the electroscope to produce a large divergence. Remove the sealing wax. Why, on the above assumptions, do the leaves again collapse? Again produce the divergence, but now touch the finger to the electroscope before removing the wax. Why do the leaves collapse? Remove the finger, then remove the wax. Why do the leaves now diverge? With the charged sealing wax find whether in charging an electroscope by induction as above the charge imparted to the electroscope is like or unlike that of the charging body. Repeat with the glass rod, and state a general rule for the sign of the charge of an electroscope which has been charged by *induction*. State the rule for charging by *conduction* (see I).

V. To show that a charge is on the surface of a conductor only. Place the inner vessel of the calorimeter of Experiment 18 on two sticks of sealing wax which rest upon the table, then

charge this vessel by rubbing over it a charged rod of any kind. Bring one of the suspended steel balls into contact with the outside of the metal vessel, then cause the ball to approach the electroscope. Has the ball received a charge? Discharge the ball with the finger, then lower it carefully into the metal vessel till it rests on the bottom. Remove it and see whether it is now charged. Record your conclusion. Why was it necessary to place the metal vessel on the sticks of sealing wax?

VI. To prove that + and − electricities appear in equal amount. (*a*) Charge a steel ball negatively and bring it carefully inside of vessel *A* (Fig. 40), which is connected by a wire to the electroscope. The divergence of the leaves will measure the charge induced on the outside of *A*. Touch the ball to the inner wall of the vessel. The divergence of the leaves is now a measure of the charge which was originally on the ball, for by V this charge has all passed to the outside. Did the divergence change at all when the ball touched the wall? What conclusion do you draw regarding the minus charge on the ball and the minus charge induced by it on the outside of the vessel?

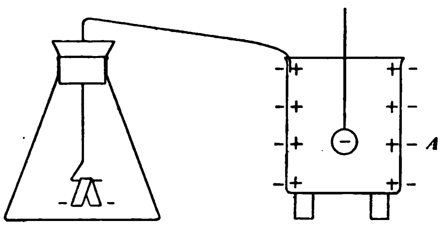


FIG. 40

(*b*) Recharge the ball and again hold it inside of *A*, without touching the wall, and note the divergence of the leaves. Touch the outside of *A* with the finger. Remove the finger, then remove the ball, but do not discharge it. Is the deflection the same as before? Test the sign of the charge on the leaves. Reinsert the ball and touch it to the vessel. Does the electroscope show any charge? What conclusion, then, do you draw regarding the − charge on the ball and the + charge which was induced on the inside of *A*?

VII. The principle of the condenser. (*a*) By means of a wire connect the electroscope with a vertical metal sheet *A* (Fig. 41), about 4 in. square, which is nailed to a piece of wood as shown. Support this on two pieces of sealing wax. Charge plate *A* by giving it a single stroke with a small piece of electrified sealing wax. If the electroscope shows any leak, rub the sealing-wax supports on a cloth until they are warm. Now move a second plate *B*, which you keep in contact with your hand, up to within about 1 mm. or 2 mm. of *A*. What effect do you find that this has on the potential of *A*? (Consider potential to be measured by the divergence of the leaves of the electroscope.)

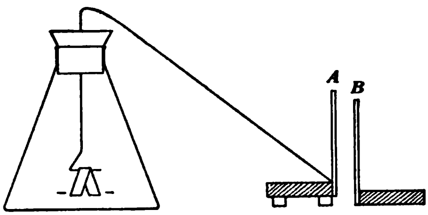


FIG. 41

(*b*) Electrify the sealing wax again, as nearly as possible in the way you did at first, and give *A* another stroke. Repeat until the original divergence is reëstablished. From the number of these strokes estimate roughly how many times the *electrical capacity* of *A* has been increased by the presence of *B*, i.e. how many times the original amount of electricity is now required to bring it to the same potential which it had at first. In view of the fact that the – charge on *A* repelled negative electricity to the earth through your finger, and thus induced a + charge on *B*, can you see why, when *B* is near by, it takes a larger charge on *A* to produce a given divergence than when *B* is remote?

(*c*) Slip a 5 in. × 5 in. glass plate between *A* and *B* and watch the electroscope. Does this increase or decrease the potential of *A*? Hence does it increase or decrease the capacity of the *condenser?*

Push the plates together until each is in contact with the glass plate. Remove the glass without changing the distance

between the plates, and charge A to a given divergence. Insert the glass and find how many more approximately equal charges may now be put on A before bringing the leaves to about the same divergence. The ratio of the charge on A when the glass was in to the charge when the glass was out is called the *specific inductive capacity* of glass.

EXPERIMENT 28

THE VOLTAIC CELL

I. Action of dilute sulphuric acid on copper and zinc strips. (*a*) *Open circuit.* Fill a tumbler two thirds full of water and add about one sixtieth as much sulphuric acid. Introduce a strip of zinc about a centimeter wide into the acid, and observe and record what effect, if any, is produced by the acid. (The bubbles are hydrogen.)

Repeat the experiment with a similar strip of copper.

Next place both the zinc and copper in the acid at the same time, but take care that they do not touch each other at any point. Observe and record the action at each plate.

(*b*) *Closed circuit.* Press the tops of the strips firmly together and notice what change, if any, takes place at the surface of each metal. Record results.

II. Effect of amalgamation. Dip the zinc plate into a dish containing a little mercury and rub the mercury over the wet portion of the zinc until it is covered with a smooth, even coat of mercury. Dip the amalgamated zinc into the sulphuric-acid solution again, and repeat the observations of I, recording what differences, if any, are observed in the action.

III. Effects observable about the wire connecting the strips. (*a*) For convenience in handling, place strips of copper and of amalgamated zinc in clamps such as those shown in Fig. 42,

and connect these clamps by means of, say, No. 24 copper wire to the binding posts of the 25-turn coil of No. 22 wire on the galvanoscope, after placing the latter with the plane of its coils north and south. Dip the metals in the acid and observe the effect on the needle.

(*b*) Disconnect the wires from the galvanoscope and touch them to the tongue. What evidence do you obtain of some

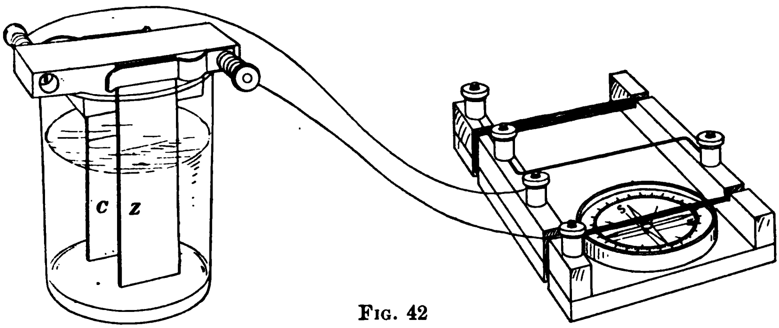


FIG. 42

action going on when the plates are in the acid, but which disappears as soon as they are lifted from it?

IV. Polarization. Take a fresh and dry copper plate, or else dry the old one by heating it in a Bunsen flame until it is much too hot to hold, and then letting it cool. Insert the zinc and copper in the clamps and connect as before to the 25-turn coil of the galvanoscope, but this time insert into the circuit about a meter of No. 36 German silver wire.[1] (No. 30 will do, but No. 36 is better.) Turn the compass until the needle points to 0°; then immerse the plates in the acid, and as soon as the needle stops swinging violently read the deflection. (If this deflection is more than 40° or 50°, slide the compass along in the

[1] For the sake of avoiding loose German silver wire, it is best to insert the meter of No. 36 wire between the binding posts *ac* of Fig. 52, and then to connect the zinc plate of the cell to *a*, the copper plate to one terminal of the galvanoscope, and the other terminal of the galvanoscope to *c*.

frame away from the 25-turn coil, until the deflection is reduced to 50° or less.) Watch the needle for a minute and record what you observe. In II you found that if the zinc is well amalgamated, hydrogen appears only at the copper plate. Short-circuit the cell for half a minute by holding a short strip of copper in contact with both the copper and the zinc plates. This simply enables the hydrogen to be generated in greater abundance. It brings the deflection nearly to *o* because most of the current now goes through the copper strip. Remove the copper strip. Does the deflection return quite to its old value? From these experiments, what effect do you conclude that the accumulation of hydrogen upon the copper plate has upon the strength of the current which the cell can furnish? This is technically called the *polarization* of the cell, and a cell in which this effect occurs is called a *polarizing* cell.

V. A nonpolarizing cell. Replace the simple cell by a Daniell cell, or construct what is essentially a Daniell cell as follows. First dry the copper plate in the Bunsen flame, then replace it in its clamp. Fill the tumbler half full of a saturated solution of *copper sulphate*, and pour *zinc sulphate* into a small porous cup, which is then to be placed inside the tumbler. Now immerse the plates in the liquids, the zinc going into the zinc sulphate in the porous cup and the copper into the copper sulphate. (The porous cup is simply to keep the two liquids separated. The electric current can pass through it with ease.) Watch the needle and record its behavior. Short-circuit the cell and see if thereafter the deflection returns to its old value. Is, then, a Daniell cell a polarizing or a nonpolarizing cell? Does the fact that the element which is deposited on the copper plate when it is immersed in copper sulphate is *copper itself* suggest to you any reason why in this case the current is not changed, as was found to be the case when the deposit was hydrogen? In which case is the character of the surface of the plate *changed* by the deposit?

VI. A polarizing commercial cell. Replace the Daniell by a Leclanché cell, if one is available (a dry cell will answer nearly as well). This consists of a zinc rod in sal ammoniac and a carbon plate inside a porous cup which is full of manganese dioxide. See first whether the current which this cell sends through the three feet of No. 36 German silver wire weakens at all in two minutes. (If the deflection is more than 45°, push the compass farther away or change to the one-turn coil.) Then short-circuit the cell for half a minute and see if thereafter the deflection returns to the old value. Is, then, this cell polarizing or nonpolarizing? Watch the needle for a minute after the cell has been short-circuited. Does the current gradually recover part of its former strength? Break the circuit entirely and let the cell stand for a few minutes; then read the deflection.

Try the same experiment with a simple cell. Record the difference in the behavior of the two cells. This difference is due to the fact that in the simple cell there is nothing to remove the film of hydrogen from the surface of the plate upon which it is deposited. In the Leclanché cell, on the other hand, the manganese dioxide slowly unites with and therefore removes the hydrogen from the carbon plate. This is indeed the object of its use. A Leclanché cell is, then, one which *recovers* on open circuit.

EXPERIMENT 29

MAGNETIC EFFECT OF A CURRENT

I. The right-hand rule, or Ampere's rule. Since a wire through which a current is flowing has just been found to deflect a magnetic needle held near it, the wire must be surrounded by magnetic lines of force. *The direction in which the*

N pole of the magnetic needle tends to move gives, by definition, the direction of these magnetic lines.

The direction in which the positive electricity flows through the circuit of a zinc-copper cell is from zinc to copper inside the liquid and from copper to zinc in the connecting wire, i.e. it flows in the direction in which the hydrogen was found to move in the last experiment. We know this because a very delicate electroscope will show that on open circuit the copper plate acquires a small + charge of static electricity and the zinc a small − charge. For this reason the copper or carbon plate of a voltaic cell is always called the plus (+) plate and the zinc the minus (−) plate. *The direction of an electric current is defined as the direction in which the positive electricity moves.*

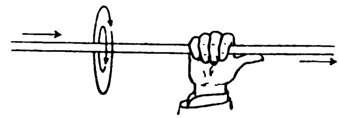


FIG. 43

By the series of experiments given below, test the following rule. *If the conductor is grasped by the right hand so that the thumb points in the direction in which the current flows, then the magnetic lines of force pass in concentric circles around the wire in the direction in which the fingers of the hand encircle it* (Fig. 43).

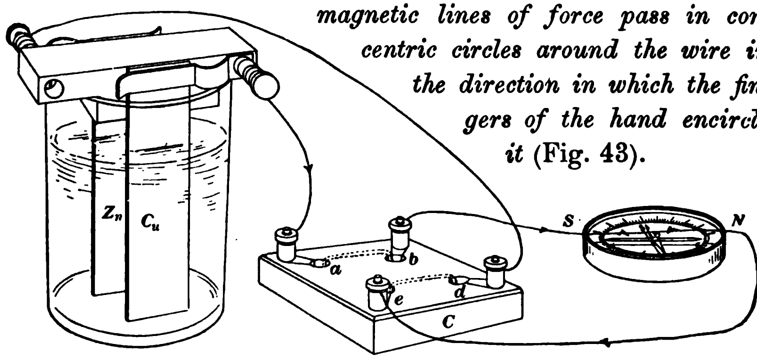


FIG. 44

(*a*) Connect either a simple cell or a dry cell in the manner shown in Fig. 44, so that the current will flow from the copper

(or carbon) through the commutator *C*, then over the needle from south to north, and back through the commutator to the zinc. All of the connecting wires should be copper, for example No. 24, and that to the right of the commutator should be 10 ft. or 12 ft. long. Insert the top of the commutator and record the direction in which the north pole of the needle turns.

(*b*) Turn the top of the commutator through 90°, so that the mercury cup *a* is connected to *e* and *b* to *d*, instead of *a* to *b* and *e* to *d*. This reverses the current in the wire so that it goes over the needle from north to south. Record the effect on the needle and compare with Ampere's rule.

(*c*) Place the compass above the wire without changing the direction of the current, and compare with the rule the effect produced on the needle. Reverse the direction of the current by means of the commutator and again compare.

(*d*) Hold the wire so that the current flows vertically *downward* just in front of the *N* pole of the compass; then cause the current to flow upward past the same pole, and test the rule in each case.

(*e*) Hold the wire so that the current flows from west to east over the middle of the needle.

Does the experiment show that the lines of magnetic force lie in planes at right angles to the direction of the wire? How?

II. To find the direction of an unknown current. Let the instructor bring a current the direction of which is unknown into the laboratory by a wire connected with a cell in a closet or in an adjoining room. Hold a compass needle near the wire and determine the direction in which the current is flowing in the wire. Record your result and then test the correctness of it by following the wire to the cell.

III. The effect of loops. (*a*) As in I, pass a current from a cell over the compass from south to north, keeping the wire

as close to the face of the compass as possible. Note the amount of deflection. Then cause the wire to return beneath the needle, so that a loop is formed, in the upper part of which the current flows past

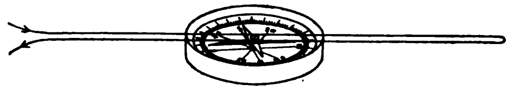


FIG. 45

the needle from south to north and in the lower part from north to south. Is the deflection greater or less than at first? Why?

(*b*) Try the effect of placing both sides of the loop above the needle, as in Fig. 45. Explain the observed effect.

(*c*) Loop the wire several times around the compass in such a way that the plane of the coil is north and south. What change is produced in the deflection by each new turn? Explain.

EXPERIMENT 30

MAGNETIC PROPERTIES OF COILS CARRYING CURRENTS

I. Magnetic effect of a helix. (*a*) Having the circuit arranged as in Fig. 44, the current being furnished either by a simple cell or by a dry cell, form a close helix (see Fig. 46) by wrapping the conducting wire forty or fifty times around a lead pencil. Then with the aid of the compass see whether or not the helix is a magnet, i.e. whether one end of it attracts the north pole while the other repels it.

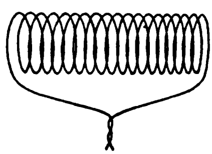


FIG. 46

(*b*) By means of the commutator reverse the direction of the current through the helix and record what effect is thus produced upon the poles.

(*c*) Test the following rule for determining the poles of a helix. *If the helix is grasped in the right hand so that the fingers are pointing in the direction in which the current is flowing in the*

coils (see Fig. 47), *the thumb will point in the direction of the magnetic lines of force, i.e. the thumb will point towards the north pole of the helix.* Show how this rule follows from Ampere's rule.

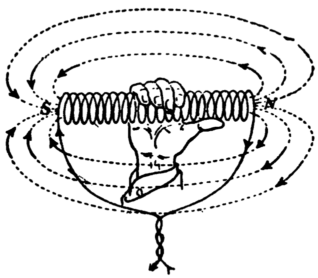


FIG. 47

II. The principle of the electro-magnet. (*a*) Thrust an unmagnetized soft iron rod, e.g. a wire nail, into the helix and then test the nail and helix together in the same way in which the helix alone was tested in the preceding experiment. Are the poles stronger or weaker than before?

(*b*) Reverse the current by means of the commutator and test and record the effect on the poles.

(*c*) Bend a piece of large iron wire into the shape of a letter U and mark one end with chalk. About the ends of both arms

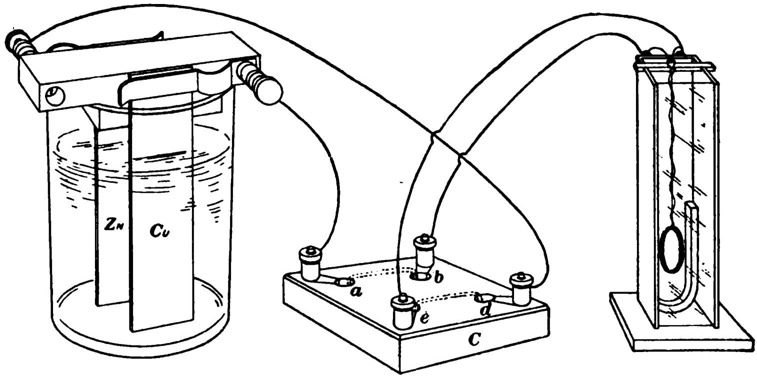


FIG. 48

of the U wind a wire carrying a current, in such a way that the marked end of the U shall be an N magnetic pole and the other an S pole. Test by means of a compass.

III. Principle of the D'Arsonval galvanometer. (*a*) Hang a coil of about one hundred and seventy-five turns of No. 32 copper wire between the poles of a horseshoe magnet in the manner shown in Fig. 48, so that the plane of the coil is parallel to the line joining the poles. The two wires which run from the coil up to the cork support should be of No. 40 insulated copper, and one of them should be twisted about the other loosely, as in the figure. Pass a current from a cell first through a commutator and then through the coil. Record the effect observed in the coil.

(*b*) Reverse the direction of the current and observe the effect produced. Explain why the coil turns as it does, remembering that it is nothing but a flat helix.

(*c*) By rotating the cork at the top, set the coil between the poles of the magnet in such a way that its plane is perpendicular to the line joining these poles. Turn on the current and note the effect.

(*d*) Reverse the current and note again the effect. Explain in each case the effect observed.

EXPERIMENT 31

ELECTROMOTIVE FORCES

In the present experiment we shall compare the *electromotive forces*, or the *electric pressures*, which cells of different form are able to maintain, by comparing the currents which they can force through a long piece of fine wire (a large resistance).

I. Effect of size of plates and distance between them on the electromotive force of a cell. To one of the terminals of the 100-turn coil of the galvanoscope connect a small coil R (Fig. 49) of German silver wire the resistance of which is about 1000 ohms. Then complete the circuit of the simple cell through this

high-resistance galvanometer in the manner shown, and read the deflection of the needle. If it is more than 20°, push the compass farther away from the coil. Lift the plates almost out of the liquid, and read again. Disconnect the wires from the binding posts of the cell, remove the frame and plates from the tumbler, press the wires very firmly against much narrower zinc and copper strips than those used before, immerse these in the liquid, and read again. Place these strips as far apart in the tumbler as you can, and see if the deflection changes as you move them together. (In all cases in which accurate readings of deflections are to be taken it is desirable to tap the frame of

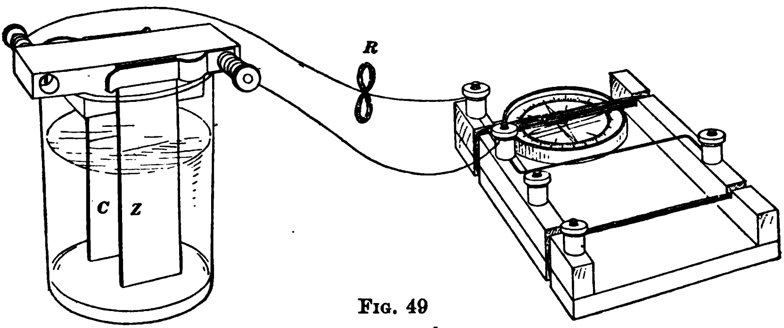


FIG. 49

the galvanometer lightly with a pencil so as to overcome any tendency which the needle may have to stick.)

What conclusions do you draw in regard to the effect of the distance between the plates and the area of immersion of the plates on the electromotive force of a cell?

II. Effect of different metal plates on the electromotive force of a cell. (*a*) Without changing anything else in the circuit, insert in the clamp of the simple cell a lead plate in place of the copper plate of the above experiment. If the needle is deflected in the same direction as before, we may know that in the external circuit the current flows from the lead to the zinc, i.e. that lead in sulphuric acid is + with respect to zinc; but

if the needle turns in the opposite direction, then the zinc is + with respect to the lead. Record tests with zinc-lead, zinc-carbon, and zinc-aluminum electrodes in the following form:

Zinc −	Copper +	Deflection 12°	Zinc ?	Lead ?	Deflection ?
Zinc ?	Carbon ?	Deflection ?	Zinc ?	Aluminum ?	Deflection ?

(*b*) Replace the zinc by a lead plate, and record tests on lead-copper, lead-aluminum, and lead-carbon thus:

Lead ?	Copper ?	Deflection ?
Lead ?	Aluminum ?	Deflection ?
Lead ?	Carbon ?	Deflection ?

Do you see any connection between the results in (*a*) and (*b*) which enables you to predict all the results in (*b*) from those in (*a*)?

If so, arrange these five substances in a list such that each substance will be positive with respect to any substance below it in the list, but negative with respect to any substance above it. Which pair give the highest E.M.F.? What conclusion do you draw in regard to the effect on the E.M.F. of the kind of plates used?

III. Effect of different liquids (electrolytes) on the E.M.F. Measure the deflection again, using the same galvanoscope, when zinc and copper are immersed (*a*) in dilute sulphuric acid (H_2SO_4); (*b*) in a solution of common salt (NaCl, i.e. sodium chloride); (*c*) in a solution of sodium carbonate (Na_2CO_3); (*d*) in common water (H_2O).

Rinse the plates thoroughly before placing them in a new liquid.

Now place copper and iron strips in the clamps of the cell, immerse in the sulphuric-acid solution, and read; then immerse the same strips in a weak solution of ammonium sulphide $(NH_4)_2S$. What effect has the change in the liquid had upon the direction of the current?

What conclusion do you draw in regard to the effect of the electrolyte on the direction and magnitude of the E.M.F. of a cell?

IV. Effect of series and parallel connection on the E.M.F. of the combination. (*a*) Connect the high-resistance circuit to

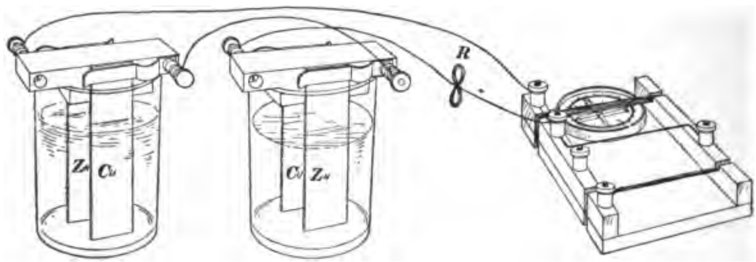


FIG. 50

the terminals of a single cell and read the deflection. If this is more that 8° or 10°, push the compass away from the coil until it is reduced to about this value. (The object of making the deflection small is to arrange the conditions so that the E.M.F. may be taken as proportional to the deflections.)

Join two similar cells in *series*, i.e. the zinc of one to the copper of the other (Fig. 50), and read the deflection when connected to the same circuit.

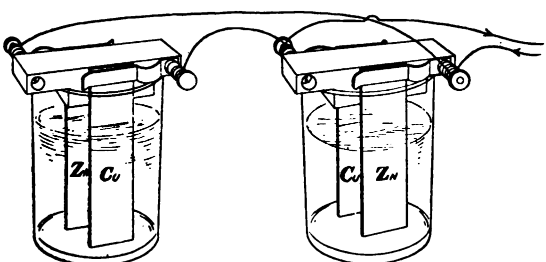


FIG. 51

(*b*) Connect the two similar cells in *parallel*, i.e. zinc to zinc and copper to copper (Fig. 51), again read the deflection, and compare with that produced by a single cell.

What conclusions do you draw in regard to the effects of series and parallel connections on E.M.F.?

V. Electromotive forces of various commercial cells. Having the galvanometer circuit arranged as in Fig. 49, reduce the deflection produced by a Daniell cell, improvised as in Experiment 28, IV, to about 10° by moving the compass away from the coil; then find the deflections produced by a dry cell, a Leclanché cell, and any other cells which you may have, and calculate the E.M.F. of all the latter cells on the assumption that the E.M.F. of a Daniell cell is 1.08 volts. In this work, however, be very careful not to change the galvanoscope in any way during any of the operations.

EXPERIMENT 32

OHM'S LAW

I. To prove that if the current remains constant in a circuit the ratio of the E.M.F. to the resistance must remain constant also. (*a*) Let the Daniell or dry cell be connected to the terminals of the high-resistance galvanoscope coil, through the 1000-ohm German silver coil, and let the deflection be carefully noted.

(*b*) Let two cells be connected in series and joined to the same high-resistance galvanoscope circuit. The deflection will, of course, be found to be much increased. Then introduce into the circuit a second precisely similar galvanoscope coil with its German silver wire in series with the one already there. Is the current reduced to its old value?

(*c*) If it is convenient, introduce three cells in series into the circuit, and see whether the introduction of a third galvanoscope coil and German silver wire will reduce the current to its old value. If the current is to be kept constant, how do these experiments show that the resistance must be increased as the E.M.F. is increased?

II. To prove that if the E.M.F. is kept constant the current will be inversely proportional to the resistance. (*a*) Pass the current from a Daniell cell through the commutator, the high-resistance coil of the galvanoscope, and the 1000-ohm coil of German silver wire, all arranged in series. If the deflection of the compass needle is more than 12° or 14°, push the compass away from the coil until its deflection is reduced to this value. Read the position of the needle carefully, both before and after reversing the direction of the current by means of the commutator.

(*b*) Introduce into the circuit a second German silver coil just like the first and a second galvanoscope coil similar to the first,

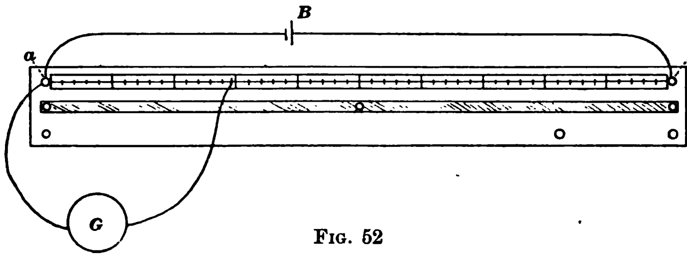


FIG. 52

all being joined in series. The resistance of these two sets of coils is obviously exactly double that of the first single set. Read the deflections of the needle before and after reversing the direction of the current. How has the current been changed by doubling the resistance?

III. To prove that when a constant current is flowing in a circuit the potential difference between any two points in the circuit is directly proportional to the resistance between these two points. (*a*) Connect a Daniell cell *B* (Fig. 52), improvised as in Experiment 28, IV, to the ends of a meter of No. 30 German silver wire mounted above a meter stick *ac*. Attach one end of the high-resistance coil of the galvanoscope *G* to the binding post *a* and press the other end firmly down upon the wire at a

point just 10 cm. from *a*. Read carefully and record the deflection. (If it is more than 4° or 5°, reduce it to this amount by pushing away the compass.) The deflection is a measure of the potential difference, i.e. the difference in electrical pressure, between the ends of this 10-cm. length of wire.

(*b*) Move the free end along to distances of 20 cm., 30 cm., and 40 cm. from *a*, and read in each position. The resistance of 20 cm. of wire is obviously twice the resistance of 10 cm., etc. What relation do you find to exist between the P.D. and the resistances across which they are taken?

The above experiment proves that no matter in what ways the resistance R. of a circuit, the current C. flowing in the circuit, or the P.D. forcing the current through the circuit, are varied, a fixed relation always exists between these three quantities, viz. current is proportional to $\frac{\text{P.D.}}{\text{R.}}$. If we define the unit of resistance as the resistance of a conductor through which one ampere of current flows when the difference in electrical pressure between its ends is one volt, then we may write the results of this experiment in the form

$$\frac{\text{P.D.}}{\text{R.}} = \text{C.}, \quad \text{or} \quad \frac{\text{volts}}{\text{ohms}} = \text{amperes.}$$

This is Ohm's law.

EXPERIMENT 33

COMPARISON OF RESISTANCES

I. To find the relative resistances of copper, iron, and German silver by the fall-of-potential method. (*a*) Wind up into a coil *C* (Fig. 53) just 3 m. of No. 30 insulated copper wire. Attach one end of it to the binding post *E*. Between the binding posts *E* and *H* stretch about 80 cm. of No. 30 iron wire, and between *H* and *F* stretch about 20 cm. of No. 30 German silver wire.

Connect the terminals of the dry or Daniell cell *B* to the points *a* and *F*. Then join the terminals of the high-resistance coil of the galvanoscope *G* so that its deflection will indicate the fall of potential through the copper coil *C* (Fig. 53). Read the deflection of the galvanoscope needle very carefully.

(*b*) Connect to *E* the end of the galvanoscope terminal which was before at *a*, and move the other terminal along the iron wire toward *H* until the P.D. between *E* and the point touched is the same as that between *a* and *E*, i.e. until the galvanoscope deflection is the same as at first. The length of iron wire

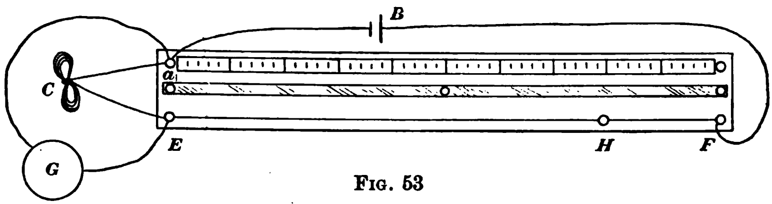


FIG. 53

between the galvanoscope terminals must then, by Ohm's law $\left(\frac{\text{P.D.}}{\text{R.}} = \text{C.}\right)$, have exactly the same resistance as the 3 m. of copper wire in the coil *C*, for, since the P.D. is the same and the current is the same, the resistance must also be the same. Find, then, by computation how many times the resistance of an iron wire exceeds that of a copper wire of the same length and diameter.

(*c*) Attach the free terminal of the galvanoscope at *F* and move the end which was before at *E* along the German silver wire until the deflection is the same as before. Compare by computation the resistance of a German silver wire with that of a copper wire of the same length and diameter.

II. To measure an unknown resistance by means of Wheatstone's bridge. If a current is made to divide, as at *a* (Fig. 54), so that part of it flows along the branch *abc* and part along the

branch *adc*, then there will be a continual fall in potential in going from *a* to *c* over each branch. Hence for any point *b* in one branch there must be a corresponding point *d* in the other branch at which the same potential exists. If these two points are connected through a galvanometer *G*, no current will flow through this galvanometer, since the same electrical pressure exists at *b* as at *d*. If the end of the connecting wire is moved a little to the right of *d*, a current will flow in one direction through *G*; while if it is moved a little to the left, a current will flow through *G* in the opposite direction. Hence, in order to find experimentally the point *d* which has the same potential as the point *b*, we have only to move the end of the galvanometer wire along the branch *adc* until we find a point at which the galvanometer shows no deflection. When this point has been found the resistance of the four branches *ad* (= *P*) *dc*, (= *Q*), *ab* (= *R*), and *bc* (= *X*) may be proved to be related in the following way:

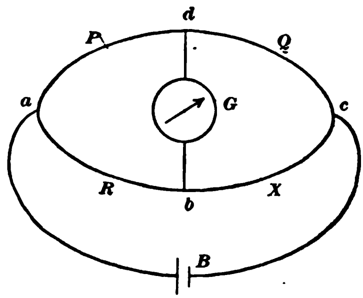


Fig. 54

$$P/Q = R/X.$$

To prove that this is so, we have only to apply Ohm's law. For if PD_1 represents the potential difference between *a* and *d*, and PD_2 that between *d* and *c*, then, since *b* and *d* have the same potential, PD_1 will also represent the potential difference between *a* and *d*, and PD_2 that between *d* and *c*. Now, by Ohm's law, since the same current C_1 is flowing through *ad* and *dc*, we have $C_1 = PD_1/P = PD_2/Q$, or $PD_1/PD_2 = P/Q$. Similarly, on the lower branch, $PD_1/PD_2 = R/X$. Therefore, $P/Q = R/X$ and $X = R \times Q/P$.

(*a*) Stretch No. 30 German silver wire between *a* and *c*, as in Fig. 55, place a meter stick beneath it, and then connect a simple or a dry cell *B* to the terminals *a* and *c*. Between the binding posts *a* and *b* insert some known resistance, say a one-ohm coil. Between *b'* and *c* insert the 3-m. coil of No. 30 copper wire used in I. The brass strap between *b* and *b'* has a negligible resistance, so that the whole of it may be considered as the point *b* of Fig. 54. Connect to the binding post at *m* one terminal of a D'Arsonval galvanometer *G*. This instrument is precisely that shown in Fig. 48, save that a slender pointer must be inserted in the place provided for it (see also Fig. 57) for the sake of making small deflections more easily observable.

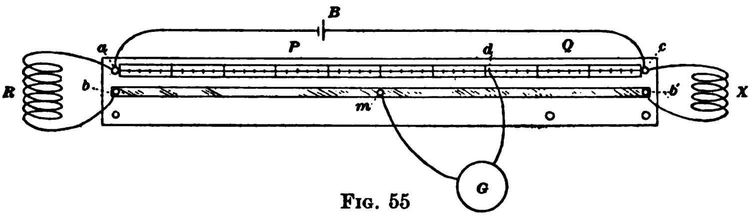


FIG. 55

Touch the free terminal of the galvanometer at a number of points along the wire *ac* until you find that point at which the galvanometer shows no deflection on making contact. Since the wire *ac* is uniform, the ratio of the resistances *P* and *Q* is simply the ratio of the lengths *ad* ($=l_1$) and *dc* ($=l_2$). Hence,

$$X/R = l_2/l_1, \text{ or } X = R \times l_2/l_1.$$

(*b*) In the same way measure the resistance of exactly 50 cm. of No. 30 iron wire, and calculate from the result the resistance in ohms of such a wire 3 m. long. By what does the value thus found for the relative resistance of iron and copper differ from that found in I?

(*c*) In the same way measure the resistance of exactly 25 cm. of No. 30 German silver wire, and compute from the result

the resistance of such a wire 3 m. long. Record the per cent of difference between this result and that found in I.

Tabulate in the form given below the final results of your measurements upon the relative resistances of the three metals, copper being taken as 1.

METAL	FALL OF POTENTIAL METHOD	BRIDGE METHOD
Copper	1	1
Iron	8.1	7.9
German silver	17.8	18.5

EXPERIMENT 34

INTERNAL RESISTANCE OF GALVANIC CELLS

I. Currents furnished by galvanic cells when the external resistance is small. In the experiment on E.M.F. (Experiment 31) we found that changing the distance between the plates, or the area of the plates immersed, had no effect on the current sent through a high-resistance coil. Try the same experiment with a low-resistance coil in the following way.

(*a*) Connect the improvised Daniell cell with the single turn of coarse copper wire which connects the middle binding posts of the galvanoscope, and observe the deflection of the compass needle.

(*b*) Lift the zinc gradually out of the cup, and record the effect. Since, as proved in Experiment 31, the E.M.F. is not diminished by decreasing the area of plates immersed, what do you conclude, from Ohm's law, must have changed in the circuit as the zinc was lifted? How, then, is the *internal resistance* affected by the size of the plates and the distance between them?

II. Current furnished by combinations of cells when the external resistance is small. (*a*) Connect a single Daniell cell with the single-turn coil of the galvanoscope. Slip the compass along until the deflection is from 6° to 10°.

(*b*) Select another Daniell cell which gives approximately the same deflection when tested in the same way. Connect the two cells in series. How does the deflection given by two Daniell cells joined in series with a small external resistance compare with that given by a single cell joined to the same external resistance? What difference do you notice between the effects here obtained and those produced in Experiment 31, where the external resistance was large?

(*c*) Connect the cells in parallel and observe the deflection. Since in Experiment 31 we showed that the E.M.F. is not changed by connecting cells in parallel, how do you explain the observed effect?

III. Measurement of the internal resistance of Daniell cells. (*a*) Join one terminal of an improvised Daniell cell to the one-turn coil of the galvanoscope, and from the second binding post of this coil run a short wire to some fixed binding post, — for example, one of the posts of the Wheatstone's bridge. Join the other terminal of the cell to about a meter of No. 24 copper wire, to the remote end of which has been attached about a meter of No. 36 bare German silver wire. First press the copper wire hard against the fixed binding post and place the compass so that the deflection is from 12° to 20°. This deflection represents the current which the cell is able to furnish when there is no appreciable resistance in the circuit except the internal resistance of the cell. Now take a half turn of the No. 36 wire about the screw of the fixed binding post and draw the copper wire away so as to include a longer and longer amount of the No. 36 wire in the circuit. When the current has been reduced in this way to exactly one half its former value, measure the

length of the German silver wire which has been introduced. Since the E.M.F. of the cell has remained the same while the current has been reduced to one half its former value, we know that the total resistance of the circuit must have been doubled. Hence, since the resistance of the copper wire is negligible, the internal resistance of the cell must be just equal to the resistance of the German silver wire which has been inserted.

(*b*) In the same way find the internal resistance of the second cell in terms of the resistance of a length of German silver wire.

(*c*) In the same way measure the internal resistance of the two cells joined in series. State what relation exists between the internal resistance of a single cell and that of two cells joined in series.

(*d*) Connect the two cells in parallel, and obtain in the same way the joint internal resistance in terms of a length of German silver wire. What relation do you find to exist between the resistance of a single cell and that of the two joined in this way? How should cells be connected in order to get as large a current as possible if the external resistance is small? if the external resistance is large?

All of the above resistances may be reduced to ohms, if desired, by taking into account the fact that No. 36 German silver wire has a resistance of 26 ohms per meter (see Appendix B).

EXPERIMENT 35

ELECTROLYSIS AND THE STORAGE BATTERY

I. Electrolysis of water. Bare the ends of two pieces of copper wire and wrap each about the head of a wire nail.[1] Connect the other ends of the wires to the terminals of two dry cells

[1] Platinum electrodes are better, but they are less convenient and much more expensive.

joined in series. Dip the ends of the nails into a dilute solution of sulphuric acid like that used in Experiment 28. Is the nail from which the bubbles appear first and most abundantly connected to the + or to the – pole of the battery, i.e. to the carbon or to the zinc? This gas, which is given off most abundantly, is hydrogen; that which appears at the other nail is oxygen. In order to account for these effects, we assume that when the molecules of sulphuric acid (H_2SO_4) go into solution in water they split up into two electrically charged atoms, or ions, of hydrogen and one oppositely charged ion of SO_4. It was this hydrogen which, according to this hypothesis, appeared at one nail while the SO_4 went to the other and there gave up an atom of oxygen. If this hypothesis is correct, must the hydrogen atom in solution carry a + or a – charge in order to appear upon the nail upon which you observed it? What kind of a charge must the SO_4 ion carry?

II. Electroplating. Remove the nails and attach each bare wire to some sort of an improvised metal clip (ordinary paper fasteners are excellent). In each of these clips place a nickel and dip the lower half of each into a solution of copper sulphate ($CuSO_4$). About which nickel do you now see bubbles, the one connected to the + or the one connected to the – pole of the battery? (The former is called the anode, the latter the cathode.) These bubbles are oxygen. After about a minute remove the nickels and dry them with a cloth. Record what has happened. Decide from your results whether the copper ions of the copper-sulphate solution carry + or – charges.

Interchange the nickels between the two clips and repeat the above operations. Record the results. (If you wish to restore your nickels quickly to their original condition, dip them for an instant in strong nitric acid and rub with an old cloth.)

III. The storage battery.[1] Arrange a simple cell in the manner shown in Fig. 56, *a* and *b* being the copper and zinc strips

[1] Two sets of students are expected to work together on this experiment.

to which are connected the terminals of an improvised voltmeter consisting of the 1000-ohm resistance coil *R* and the galvanoscope *V*, with the compass beneath its high-resistance coil. *A* is an improvised ammeter consisting of another galvanoscope with the compass beneath the 25-turn coil of coarse wire; *r* is a resistance of about 100 ohms (use for it the 100-turn coil of No. 40 wire of the same galvanoscope used for *A*); *B* is a battery of two dry cells connected in series but *not* joined, at first, to the terminals *m* and *n* of the cell circuit. Move the compass of *V* until the deflection is 8° or 10°. This amount of deflection then represents the E.M.F. of a copper-zinc-sulphuric-acid cell, viz. approximately 1 volt.

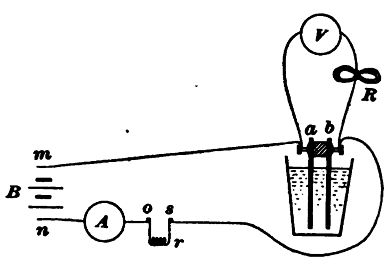


FIG. 56

Now replace the zinc and copper strips by two strips of sheet lead. Does the voltmeter *V* now indicate any E.M.F.? Explain the reason. Next connect *m* and *n* to the terminals of the dry battery *B*, and as soon as the needles are sufficiently quiet record the deflections shown by both *A* and *V*; then watch both needles carefully for about two minutes, and record the readings, expressing the reading of *A* simply in scale divisions, but that of *V* in both scale divisions and volts.

Now short-circuit the terminals *o* and *s* of the resistance *r* by pressing a strip of metal against the two binding posts *o* and *s* or by connecting them with a copper wire. Watch the plates and note the hydrogen appearing in considerable quantity about the cathode, while but little oxygen appears about the anode. After the current has been running through the short circuit on *r* for about two minutes lift the plates from the liquid. Do you see a faint reddish deposit upon the anode where the oxygen would naturally have appeared? If not, let the current run a little

longer and observe again. This deposit is *lead peroxide*. Why, then, did so little oxygen gas appear about the anode?

Replace the plates in the acid, take away the shunt from *os*, and record the reading of *V*. By how many volts is it now larger than it was when *m* and *n* were first joined to *B*? Disconnect *m* and *n* from *B*, and observe how many volts of E.M.F. have been developed between the lead plates. Now watch the ammeter as you join *m* and *n* to each other. What is the direction of the observed current with reference to that which the battery sent through the ammeter? Watch the voltmeter and ammeter for two minutes while the *storage cell* is discharging. In view of this back E.M.F. which the experiment has shown was developed in the lead cell by the deposit of lead peroxide on the anode, explain why during the *charging* of the storage cell the voltmeter deflection *rose*, while that of the ammeter *fell*. From your experiment, decide how many volts are required to charge a storage cell.[1]

EXPERIMENT 36

INDUCED CURRENTS

I. Induction of currents by magnets. (*a*) Set up the D'Arsonval galvanometer (Fig. 57), and insert in the place provided for it a slender wire or broom-corn pointer in the manner shown in the figure. Short-circuit a simple cell by means of a few feet of copper wire; then to the galvanometer terminals touch wires which are connected to the cell and note the direction of deflection. (The object of the short-circuiting is to prevent a too violent throw of the coil.) Record the terminal (right or left) of the galvanometer at which the current entered it when the deflection was in a given direction (right or left). This will enable

[1] If you wish to repeat the experiment with the same lead plates, you should first clean them very thoroughly with sandpaper.

you henceforth to know at which terminal any current enters your galvanometer, as soon as you observe the direction of deflection. Connect to the galvanometer a 600- or 700-turn coil *A* of No. 27 copper wire. Take particular pains to scrape the ends of all wires which are to be joined, and to twist the scraped ends firmly together.

Thrust the coil *A* suddenly over the north pole of the bar magnet, and note and record the direction and the approximate amount of the deflection of the end of the pointer attached to the coil. A paper scale supported between the walls beneath the pointer will enable you to estimate amounts.

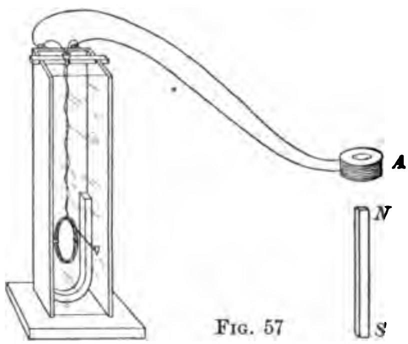


FIG. 57

(*b*) From the direction of the deflection, determine the direction of the current induced in the coil of wire thrust over the pole. While this induced current was flowing did it make the end of the coil, considered as a temporary magnet (see Experiment 30), which was approaching the *N* pole itself an *N* or an *S* pole?

(*c*) Suddenly withdraw the coil from the magnet. Note and record as before the direction and amount of deflection. How does the direction and amount of the induced current now compare with that found in (*a*)? Is the end of the coil which leaves the magnet last of the same sign as the pole of the magnet or of unlike sign?

(*d*) Draw in your notebook four figures like those shown in Fig. 58, and insert in each the signs of the poles of the coil due to the induced current, when the coil is in the four positions indicated in the figures and moving in the directions indicated by the arrows.

(*e*) Repeat the same experiments with the *S* pole of the magnet, and observe in each case the direction of deflection and the direction of the current induced in the coil. Is the nature of the induced magnetism of the coil *A* in every case such as to *oppose* or to *assist* the motion of the coil?

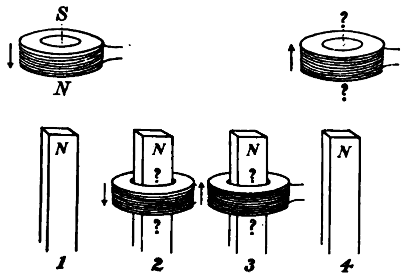


FIG. 58

II. Induction of currents by electro-magnets. (*a*) Slip the 700-turn coil used in I over an iron bar (e.g. one of the tripod rods) and connect it through a commutator with a battery *B* of one or two dry cells, in the manner shown in Fig. 59. Place a second similar coil over this bar and connect it with the D'Arsonval galvanometer as shown. Now *make* the circuit by inserting the upper part of the commutator, and record

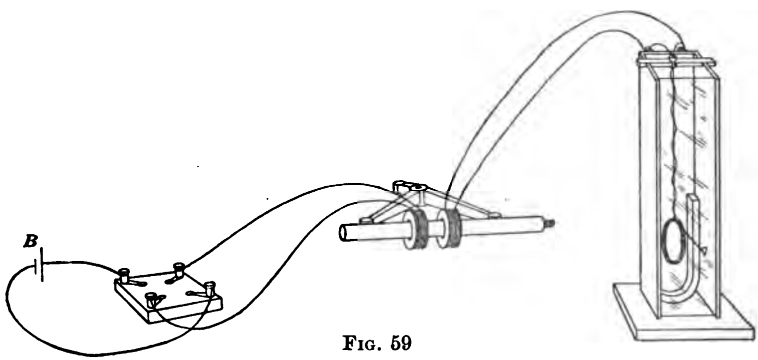


FIG. 59

the effect produced upon the needle. From the direction of deflection of the pointer, find the direction in which the current flowed around the iron core in the coil attached to the galvanometer (the so-called *secondary*). Was the induced current in the same or in the opposite direction to that in which the current

from the cell is circulating around the core in the *primary* coil? What connection do you find between this experiment and I?

(*b*) Remove the commutator top and thus *break* the circuit in the primary. Note the direction and amount of deflection, and compare with that observed when the current was *made*. Compare the direction of the induced current in the secondary with that which was flowing in the primary. Is the current in the secondary circuit produced by the magnetism of the electro-magnet or by changes in the magnetism of the electro-magnet? Do the induced currents in every case tend to assist or to oppose the changes which are taking place in the magnetism of the core?

(*c*) Push up the base of the tripod into contact with the rod (Fig. 59), so that the magnetic lines can have a return *iron* path instead of a return *air* path. Observe the amount of the deflection at make or break and compare with the amount when the tripod base is removed. (The difference will not be large, but it will be easily observable.)

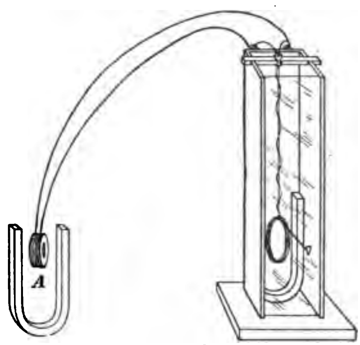


FIG. 60

III. Principles of the dynamo and motor. (*a*) Hold the coil *A* between the poles of a horseshoe magnet (Fig. 60), and in such a position that its plane is *perpendicular* to a line joining the poles. Rotate quickly through 90°, i.e. to a position in which its plane is *parallel* to the lines of force. Observe the direction of deflection of the suspended coil.

(*b*) After the pointer has come to rest rotate the coil *A* 90° more, and note and record the direction of deflection.

(*c*) Similarly, rotate the coil through the next two quadrants.

(*d*) If the coil were to be rotated continuously in this way, what portions of the rotation would produce a current in one direction, and what in the opposite direction? In what position of the coil will the induced current change from one direction to the other?

(*e*) In a dynamo a coil is forced to rotate in the strong field of an electro-magnet and induced currents are produced. In a motor currents are sent through a coil which is in a strong magnetic field and the coil is forced to rotate. Point out the parts of the above apparatus which correspond to the dynamo, and those which correspond to the motor.

EXPERIMENT 37

ELECTRIC BELLS AND MOTORS

I. Study of electric bells. (*a*) Connect an electric bell with a dry cell, and with an inexpensive compass test the condition of the electro-magnet first when the clapper is held against the bell, then when it is held away from it. Trace the current through the instrument and, with the aid of a rough diagram, explain in your notebook why the bell rings.

(*b*) Connect a bell, two push buttons, and a cell in such a way that pushing either button will ring the bell.

FIG. 61

II. Study of a small motor. (*a*) Join two dry cells in series to a small motor (Fig. 61). As soon as the motor begins to run determine with a small compass needle which is the *N* and which the *S* pole of the field magnets. Trace out the winding of the field magnet, and determine from the rule of Experiment 30 which pole should be *N* and which *S*. Do the calculated and observed signs agree?

(*b*) Stop the motor and trace the wires leading into one coil of the armature. Find from the rule what should be the sign of its magnetism at two or three different points in a revolution. Test at each point with the compass. Notice particularly the points at which its magnetism reverses. Hence, account in your notebook for the continuous rotation and for the observed direction of rotation of the motor.

(*c*) From a study of the windings, decide whether or not interchanging the battery terminals would reverse the direction in which the motor runs. Record the answer in your notebook, and then test the correctness of your conclusion by experiment.

EXPERIMENT 38

SPEED OF SOUND IN AIR

A. Let the class be divided into two sections and placed exactly a kilometer apart, the distance being measured by laying off fifty times the length of a cord 20 m. long. Each group should be provided with a pistol, blank cartridges, and at least one stop watch. Let a member of one group raise and lower a handkerchief three times as a ready signal, and simultaneously with the last lowering let him fire a pistol. Let a member of the other group take with a stop watch the time which elapses between the flash and the report of the pistol. Then let the operations at the two stations be interchanged, in order to eliminate the effect of any wind which may be blowing. In this way take six or more observations, different members of the class timing the interval in turn. Observations which differ badly from the general average and which are evidently the result of awkward handling of the stop watch need not be included in the final mean. From this mean, compute the velocity of sound at the temperature of the air.

B.[1] If stop watches are not available, set up a heavy pendulum which beats seconds; attach some white object to it; set up a screen so that the pendulum can be seen only when it is passing the middle point of its swing; let one student stationed near the pendulum pound loudly on some sonorous object at each instant at which the pendulum crosses the middle point, and let the class move away until the beats of the hammer appear again to coincide with the passages of the pendulum. The distance from the class to the pendulum is obviously numerically equal to the velocity of sound.

EXPERIMENT 39

VIBRATION NUMBER OF A FORK[2]

(*a*) Smoke the glass plate *A* (Fig. 62) by holding it in the flame of burning gum camphor or in a gas flame.[3] Keep the plate moving back and forth so that it will not become overheated in one place and crack. Lay the plate on the board,

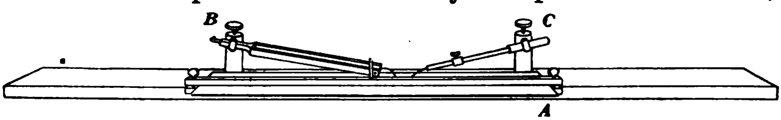


FIG. 62

smoked side up, and adjust the two styluses by means of the clamps *B* and *C* until they touch the plate lightly, very near each other in the line in which the motion is to take place.

[1] As in Experiment 13, *A* and *B* are intended as alternatives, the choice depending upon equipment.

[2] One "vibration-rate apparatus" and fifteen glass plates will suffice for a class of thirty. It is recommended that the instructor make the traces, and that the students take the measurements.

[3] Instead of smoking the plate the authors often mix up a paste of whiting or chalk dust in alcohol and paint the plate with it. This brings out the trace as well, and the whiting is very much cleaner than lampblack.

Set the fork into vibration by striking it with a wooden mallet, or bowing with a violin bow, and as soon thereafter as possible start the bob to vibrating, and draw the plate beneath the bob with such rapidity that the trace of three or four complete vibrations of the bob will appear on the plate.

(*b*) Count the number of vibrations of the fork corresponding to a full vibration of the bob, i.e. the number of vibrations of the fork between the points A and C (Fig. 63), then between B and

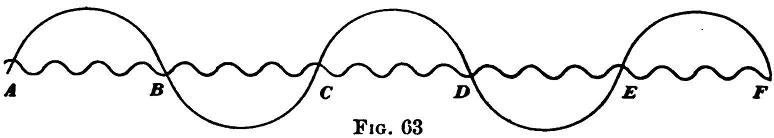


FIG. 63

D, then between C and E, then between D and F, etc., estimating in every case to tenths of a vibration. Take a mean of these counts as the number of vibrations of the fork to one of the bob.

(*c*) Repeat the observations on two other traces, and take the mean of the three means as the correct value of the number of vibrations of the fork to one of the bob.

(*d*) Get the rate of the bob by counting with the aid of an ordinary watch the number of vibrations which it makes in one or two minutes.

(*e*) Compute the number of full vibrations made by the fork per second. Tabulate thus:

	First trace	*Second trace*	*Third trace*	*Number vibrations of bob*
Vibrations between A and C =	——	——	——	——
Vibrations between B and D =	——	——	——	——
Vibrations between C and E =	——	——	——	——
Vibrations between D and F =	——	——	——	——
Means =	——	——	——	——

Final mean = ——

Number vibrations of bob per second = ——

∴ Rate of fork = ——

EXPERIMENT 40

WAVE LENGTH OF A NOTE OF A TUNING FORK

(*a*) Let one student strike a C′ fork (i.e. one which makes 512 vibrations per second) upon a block of wood, and then quickly hold it above the tube of Fig. 64, with the flat face of one prong just above the end of the tube. (Use the tube of Fig. 11, p. 14.) Let a second student raise and lower the vessel *A* while the fork is sounding, and note as accurately as possible the shortest length of maximum resonance. Mark this position by means of a small rubber band. Test the correctness of the setting by several observations.

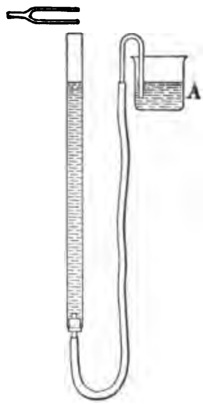


Fig. 64

(*b*) Locate in the same way a second position of resonance lower in the tube, and mark with a rubber band as above. Since the distance between two positions of maximum resonance is exactly one half wave length, twice the distance between the rubber bands will be equal to the wave length of the note sent forth by the sounding tuning fork. Compare this value of the wave length with that computed by dividing the speed of sound at the temperature of the room by the vibration number of the fork as marked upon it. (Speed of sound in air at 0° C. = 332 m. per second. It increases 60 cm. for each degree rise in temperature.)

(*c*) Find in the same way the wave length of a fork one octave lower than the first. Tabulate results thus:

	First resonant length l_1	*Second resonant length* l_2	*Difference* × *2* $= \lambda$
Fork No. 1	= ——	——	——
Fork No. 2	= ——	——	——

Number vibrations of fork No. 1 = —— ∴ Calculated wave length = ——
Number vibrations of fork No. 2 = —— ∴ Calculated wave length = ——

State in notebook how you have proceeded to find λ.

Show how this method might be used for finding the velocity of sound.

Since the speed of sound is the same for notes of all pitches, what conclusion can you draw from your experiment in regard to the vibration frequencies of two notes which are an octave apart?

EXPERIMENT 41

LAWS OF VIBRATING STRINGS

I. Effect of length on the vibration rate of a stretched wire. (*a*) Stretch a fine steel piano wire (No. 00) along the board *A*

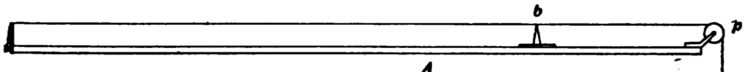
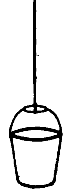


Fig. 65



(Fig. 65), insert a bridge at *b*, and hang a pail having a capacity of at least six quarts over the pulley *p*. Pour water into the pail until the note given by the wire (best picked near the middle) is in unison with the note of the lowest fork provided, viz. C. Measure carefully the length of the wire between the fixed end and *b*.

(*b*) Move the bridge *b* until the note given by the wire is exactly in tune with a fork C′, an octave higher than the first one. Measure and record the length from the fixed end to *b*.

(*c*) In the same way (i.e. by moving *b*) tune the wire to unison with a third fork, e.g. G above middle C, and measure and record the corresponding length.

(*d*) From a study of the measured lengths and of the vibration numbers as marked on the forks, find and state in your notebook the law connecting the rate of a vibrating string with its length when the tension is kept constant.

II. Effect of tension on the vibration rate of a stretched wire. (*a*) Set up side by side two boards like *A* (Fig. 65), both of which are provided with No. 00 piano wire. Place the bridges *b* at the same distance, say 60 cm. from the left end of each. Produce the same tension in the two wires by hanging from each a like weight, for example a pail containing a small amount of water. The weights should be of such size as to produce in the plucked wires a low but perfectly distinct musical note. Bring the two wires into exact unison by adjusting the water in one of the pails until no beats are heard when the strings are sounded together. Find the exact tension on one of the wires by weighing the pail and water carefully with a spring balance. Produce the exact octave on the other wire by moving the bridge until the wire is only one half as long as at first. Bring the first wire into unison with it by adding water to the pail, leaving the length exactly as at first. Weigh the pail and water again, and find the ratio of the weights in the two cases. In order to double the rate, how many times has it been necessary to multiply the stretching force?

(*b*) Make the second wire just two thirds its original length, its tension still being kept constant. In what ratio will this change its vibration number? Adjust the amount of water in the pail hanging from the first wire until the two are in unison, and weigh on the spring balance again.

From the law suggested in *a*, calculate what this last stretching weight should have been, and see how well it agrees with the observed value.

Tabulate results thus:

I.	Length of C wire	= —— cm.
	Length of C′ wire	= —— cm.
	Length of G wire	= —— cm.
	Calculated length of C′ wire	= —— cm.
	Calculated length of G wire	= —— cm.

II. First stretching weight = —— g.
Second stretching weight = —— g.
Second divided by first = —— g.

Third stretching weight (calculated) = —— g.
Third stretching weight (observed) = —— g.

State in notebook the laws discovered in I and II.

EXPERIMENT 42

LAWS OF REFLECTION FROM PLANE MIRRORS

I. To prove that angle of incidence equals angle of reflection. (*a*) Blacken one side of a strip of plate glass or a microscope slide; attach it by means of a rubber band to a small wooden block, and then set it on edge so that the line *AC* (Fig. 66), drawn on a sheet of paper, coincides with the plane of the unblackened face. The rear face is blackened in order to prevent reflection from that face and enable one to work with the light reflected from the front face alone. Set a pin at a point *B* against the face of the glass. Set another pin at any point *P*, and then, placing the eye so as to sight along *B* and *P''*, the image of *P*, set a third pin *P'* somewhere in this line of sight. Remove the glass plate and with a protractor or a pair of dividers construct a perpendicular *BE* to *AC* at the point *B*. Draw *PB* and *P'B* and measure the angle of incidence *PBE* and the angle of reflection *P'BE* with the protractor. If a protractor is not at hand, draw an arc with *B* as center, cutting the lines *PB* and *P'B* at *M* and *O*, and measure the lines *MN* and *ON*.

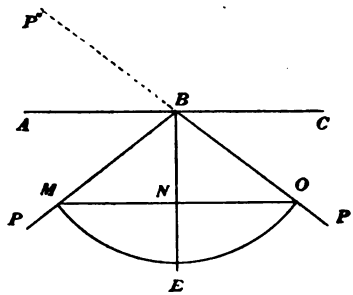


FIG. 66

(*b*) Repeat for some other position of P.

(*c*) Finally set P at such a point that it is directly in line with its own image P'' and B. Draw the line PB and also construct the perpendicular to AC at B. If the angle of incidence is equal to the angle of reflection, the two lines should exactly coincide.

II. To locate the image formed by a plane mirror. (*a*) Again set up the pin at P (Fig. 67), draw the line AC, and place the edge of the mirror upon it, then lay a straight-edge on the paper in successive positions ab, cd, ef, etc., such that the image P'' always appears to lie in the prolongation of the edge of the ruler. Draw the corresponding lines, ab, cd, etc.; then remove the glass and locate the image P'' by prolonging these lines to their point of intersection.

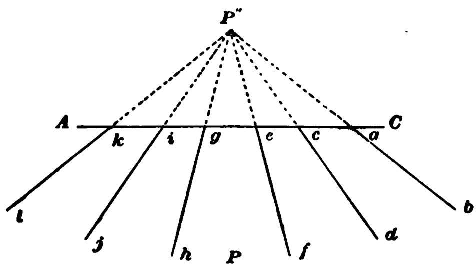


FIG. 67

(*b*) Measure the perpendicular distance from P to AC and from P'' to AC. Also measure the angle which PP'' makes with AC.

Tabulate your results neatly, and state the conclusions which you draw from I and II.

EXPERIMENT 43

TO FIND THE RATIO OF THE VELOCITIES OF LIGHT IN AIR AND GLASS

(*Index of refraction of glass*)

Draw a straight line AC (Fig. 68) across a large sheet of paper, and set one edge of the plate-glass prism mnO in exact coincidence with it. Lay a ruler on the paper in such a position

that, as you sight along its edge from some position E in the plane mnO, the apex O of the prism, as seen in the face mn, appears to lie in the prolongation of the edge of the ruler. Draw a fine line ab along this edge. Then move the eye to a position E', about as far to the right as E was to the left of the normal to mn, and draw in the same way a line cd. Mark the position of O carefully by means of a pin prick. Then remove the prism, and with an accurate straightedge and a very sharp pencil or knife edge prolong ab and cd until they meet in some point O'. The point O is then the center *in the glass* of the light waves by means of which you see the apex O, while the point O' is the center of the same waves *after they have emerged into air.* If, therefore, from O and O' as centers, the two arcs qrt and $qr't$ are constructed, the arc qrt would represent the shape and position of the wave from O when it has reached the points q and t, if the speed in air were the same as the speed in glass, while $qr't$ is the actual position of this wave in view of the fact that light travels faster in air than in glass. sr'/sr is then the ratio of these two speeds. But sr'/sr is also the ratio of the *curvatures* of the arcs $qr't$ and qrt, i.e. it is the ratio of the amounts by which these curved lines depart from the straight line qst. Now if, at a given point, one arc is curving twice as rapidly as another, it is evident that its center can be but half as far away, i.e. the curvatures of two arcs are always inversely proportional to their radii. Hence the ratio sr'/sr is the same as the ratio $Oq/O'q$.

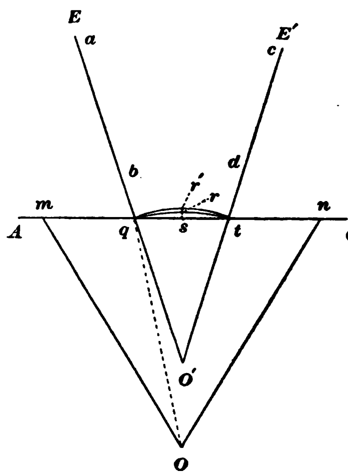


FIG. 68

Measure these distances as carefully as possible with a meter stick, and record your value for the ratio of the velocities of light in air and glass. This is called the *index of refraction of glass.* Repeat the observations, using different positions of E and E', and see how well the two observations agree.

Record your results as follows:

First trial		*Second trial*	
Oq	= ——	Oq	= ——
$O'q$	= ——	$O'q$	= ——
Index	= ——	Index	= ——

Per cent of difference between first and second = ——
Mean value of index = ——

EXPERIMENT 44

THE CRITICAL ANGLE OF GLASS

Place the plate-glass prism ABC (Fig. 69), having three polished faces, upon a large sheet of paper in front of a window OR through which the sky is visible. If desired, OR may be a piece of ground glass behind which a white light is placed. Place the eye in a position E, so as to observe the image of the sky or ground glass as it is seen by reflection from AB. A bluish-green line will be seen dividing AB into two parts of markedly different brightness.

The part to the right is brighter than the part to the left. If this line dividing the field is not seen at first, it will appear on moving the eye to the left or right. Move the eye about until the green edge of this line is brought into exact coincidence with a small ink spot placed at s on the face AB. From the figure, it will appear that the light which comes to the eye by reflection from the various points along AB must make a larger and larger angle of incidence on AB as the point considered lies farther and farther to the right of A. When this

angle is equal to or greater than the critical angle, as is the case between *s* and *B*, the whole of the light incident upon *AB* is reflected; when it is less than the critical angle, as is the case between *A* and *s*, part is reflected and part transmitted. The blue-green line which separates the field into parts of unequal brightness represents the position on *AB* at which total reflection begins, i.e. the angle *i* is the critical angle for glass. To measure this angle, lay a ruler so that its edge appears to lie in the same straight line with the point *s* and the green edge of the

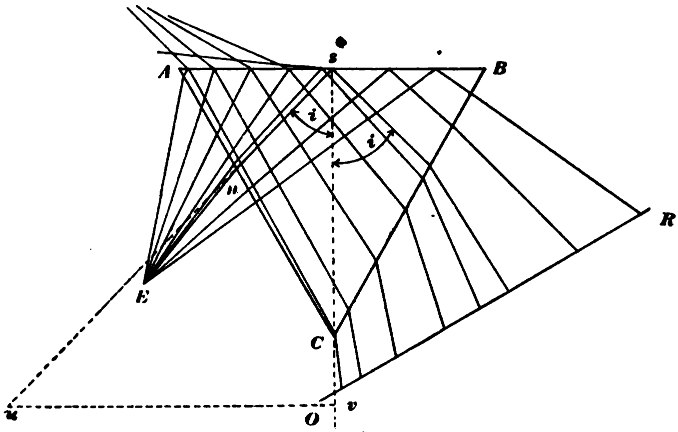


FIG. 69

line in the field, and mark with a line on the paper the position of the straightedge. Then with a sharp pencil or a knife draw an outline *ABC* of the prism upon the paper, and place a pin prick at *s* just beneath the ink spot *s* on the face *AB*. Remove the prism and extend the line just drawn until it meets *AC* at some point *n*. Connect this point *n* with the pin prick at *s*, erect the perpendicular upon *AB* at *s*, and measure with the protractor the angle *i*. This is the critical angle for glass.

Extend the lines *sn* and the perpendicular at *s* so as to make them from 6 in. to 1 ft. in length. Draw *uv* parallel to *AB*.

Then us/uv should give the same value for the index of refraction as that obtained in the last experiment. The proof of this statement is not suitable for an elementary text, but the measurement will furnish an interesting check as to the accuracy of the results of the experiment.

EXPERIMENT 45

FOCAL LENGTH OF A CONCAVE MIRROR

I. Support the concave mirror by means of a clamp in direct sunlight, and let the image of the sun be thrown upon a narrow strip of paper held in front of the mirror. Measure the distance from the mirror to the point at which the spot of light on the thin strip is smallest and brightest. This distance is the focal length. Designate it by the letter f.

II. Throw the image of a distant house on the thin strip of paper in the same way. Repeat the above measurement.

III. Place a candle flame or an electric light about 25 cm. or 30 cm. from the mirror and locate the position of the image by letting it fall on the narrow screen. Compute the focal length from the formula

$$\frac{1}{u}+\frac{1}{v}=\frac{1}{f},$$

in which u and v are the distances of the object and image respectively from the center of the mirror.

IV. Set up a pin on a block so that its head is about opposite the middle of the mirror. Move the pin out to about twice the focal distance from the mirror. If the eye is placed in front of the mirror and as much as 8 in. or 10 in. farther from it than the pin, the object and image may both be seen, the image inverted and the object erect in the manner shown in another connection in Fig. 71. Shift the position of the pin or of the

mirror until the image of the head of the pin is exactly in line with the head of the pin itself. Move the eye to right and left and see whether there is any relative motion of the pin and its image. If so, it is because they are not the same distance from the eye. The one which is farther away will move to the left when the eye is moved to the left, and to the right when the eye is moved to the right. (Test the correctness of the above statement by holding two pencils in line, but at different distances from the eye, and noticing how they appear to move with reference to each other as the eye is moved from side to side.) Adjust the position of the pin until there is no relative motion between the pin and its image as the eye is moved from side to side. The image of the pin is now at the same place as the pin itself, hence the pin must be at the center of curvature of the mirror. Measure the distance from pin to mirror. This distance is *the radius of curvature of the mirror.* Find what relation exists between this distance and the focal length of the mirror.

Record results as follows:

Focal length, by I = ——	Focal length, by III = ——
Focal length, by II = ——	½ radius of mirror = ——

EXPERIMENT 46

LAWS OF IMAGE FORMATION IN CONVEX LENSES

I. Set up in the positions shown in Fig. 70 a wire netting O, a reading glass L of about 15 cm. focus, and a block B provided with a paper scale s. Set a gas flame behind O to insure bright illumination. Adjust B and L until the image of the netting is sharply outlined on s. Then measure u, the distance from O to the middle of the lens L, and v, the distance from L to s. Next read on s the number of millimeters covered by ten

or twenty squares in the image of the netting. Then with another scale measure the number of millimeters covered by the same number of squares on the netting O. These two observations give respectively the length L' of the image and the length L of the object. Repeat the same

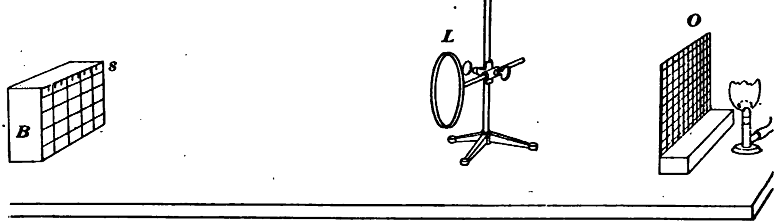


FIG. 70

observations with three or four different values of u, such as 30 cm., 40 cm., 50 cm., and 60 cm., and calculate the focal length f of the lens from the formula

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}.$$

Also take the ratios L/L' and u/v and tabulate as follows:

u	v	$\frac{1}{u}+\frac{1}{v}$	f	L	L'	$\frac{L}{L'}$	$\frac{u}{v}$

What conclusion do you draw from the last two columns?

II. Find the focal length of the lens directly by removing O and casting the image of a distant chimney or house upon *s*.

III. As a final check on the focal length, place a plane mirror behind the lens and mount a pin in front of the lens opposite its center. Adjust the pin by the method of parallax (the method used in IV, Experiment 45) until the image of the head of the pin coincides with the head of the pin itself. The distance from the pin to the center of the lens must then be equal to the focal length of the lens, as is shown by the diagram (Fig. 71), since the waves between the lens and the mirror are plane.

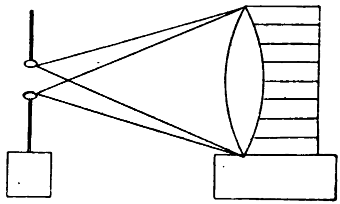


FIG. 71

Compare the results of II and III with the fourth column above.

EXPERIMENT 47

MAGNIFYING POWER OF A SIMPLE LENS

Fig. 72 shows a so-called linen tester, — a simple lens at the focus of which is a square hole in a brass frame. Lay one meter stick on the table (see the figure), and with the aid of another one held vertically, adjust the position of the eye which is viewing the horizontal stick so that the distance from the stick to the eye is just 25 cm. Then, keeping the head always in this position, bring up the lens as close as possible to the other eye. Keep both eyes open at the same time and observe how many millimeters on the stick seen with one eye are covered by the hole seen through the lens with the other eye. Divide the number by the measured width of the hole in

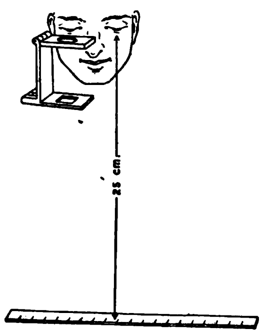


FIG. 72

millimeters. This is obviously the magnifying power of the simple lens, since it shows how many times larger the object appears when seen through the lens than when viewed with the naked eye at the distance of most distinct vision, viz. 25 cm. Measure as accurately as possible the focal length f of the lens, i.e. the distance from the middle of the lens to the hole, and see how well the observed magnifying power agrees with the theoretical value, viz. $25/f$.

EXPERIMENT 48

THE ASTRONOMICAL TELESCOPE

I. To construct a telescope. With the simple magnifying glass used in the last experiment, and an objective consisting of the reading glass of Experiment 46, construct an astronomical telescope as follows. Set the reading glass in some support (Fig. 73) and find, with the aid of a piece of white cardboard, the distance from the lens at which the image of a distant building or window is formed. Then set up the linen tester behind the card at its focal length from it. Now remove the card and view the image of the distant object through the eyepiece. Slide the eyepiece support, if necessary, until the distant object, preferably a brick wall, is very sharply seen; then measure the distance between the lenses and compare this distance with the sum

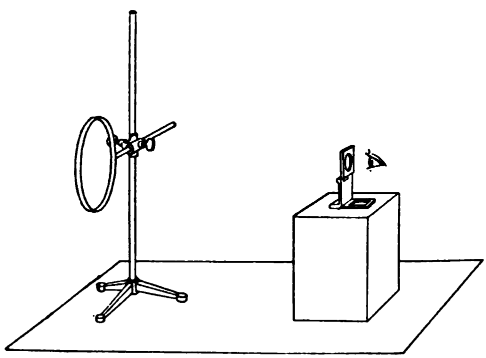


FIG. 73

of the focal lengths. Do you find any simple relation between these quantities? Can you see any reason why there should be some such relation? Explain.

II. To measure the magnifying power of the telescope. Focus the telescope upon two heavy horizontal marks drawn, for example, on a blackboard on the opposite side of the room. Let the lines be from 3 in. to 6 in. apart. When the lenses have been adjusted so that a distinct image of the marks is seen with the eye which is looking through the telescope, open the other eye and direct another student to make marks on the board which shall coincide with the apparent positions on the board of the images of the two marks as seen through the telescope. It may be found difficult at first to give attention to both eyes at once, but a little practice will make it easy. Repeat several times and compute the magnifying power from each observation. Compare this magnifying power with the theoretical value for the magnifying power of a telescope, i.e. the ratio of the focal lengths of the objective and eyepiece. (These were found in Experiments 46 and 47.)

EXPERIMENT 49

THE COMPOUND MICROSCOPE

I. To construct a microscope. Place two corks which contain holes about 1 cm. in diameter in the ends of a cardboard or tin tube 4 in. or 5 in. long, and with the aid of a rubber band fix the lenses of two of the linen testers over the holes (Fig. 74). Support the tube vertically over the table by means of clamps, and raise or lower it until a magnified image of a millimeter scale lying on a block beneath it is in sharp focus, the distance from the table to the top of the tube being somewhat more than 25 cm.

II. To determine its magnifying power. Lay a meter stick on the table, as in Fig. 74, and elevate one end of it until the distance from the eye which is not looking through the microscope to the stick is exactly 25 cm. By fixing the attention simultaneously on the two scales seen, one through the microscope and the other with the unaided eye, determine how many millimeters on the meter stick are covered by 1 mm. of the scale seen in the microscope, i.e. find the number of "diameters" of magnification of the microscope. If l_1 is the distance from the objective to the focal plane of the eyepiece, i.e. the distance between the centers of the lenses minus the focal length f of the eyepiece, and if l_2 represents the distance from the objective to the object viewed, then l_1/l_2 represents how many times the image formed by the objective is larger than the object. Since the eyepiece magnifies this image $25/f$ times, the total magnifying power of the compound microscope should be $25/f \times l_1/l_2$. Measure l_1 and l_2 and compare the observed value with this calculated value, and tabulate the results in neat form.

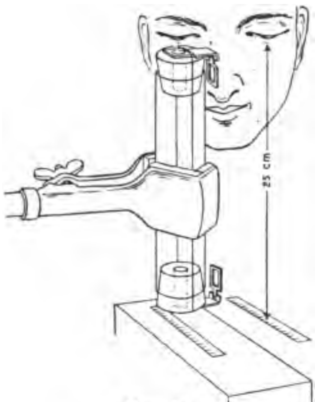


Fig. 74

EXPERIMENT 50

PRISMS

I. Path of a beam of light through a prism. Draw a line AC (Fig. 75) on a page of your notebook. Place the prism on the paper in the position indicated in the figure. Light coming to the prism in the direction AC will be bent both upon entering and leaving the prism. Place a straightedge on the paper and

adjust it carefully until it is exactly in line with the apparent direction of AC as seen through the prism. With a sharp pencil draw a line DE along the edge of the ruler, and trace the outline of the prism on the paper. Remove the prism and extend the lines AC and DE until they meet, at f and g, the lines which represent the prism faces. Then $AfgE$ will be the path of the light which traverses the prism.

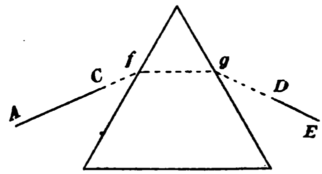


FIG. 75

II. Dispersion. (*a*) With the aid of the knowledge gained in I, place the prism in direct sunlight in such a way that the beam from the sun is thrown upon some shaded portion of the floor. Place between the prism and the sun a sheet of cardboard containing a horizontal slit 2 mm. or 3 mm. wide. Name the colors which you see upon the floor and into which the sunlight has been resolved. Which has suffered the largest bending in passing through the prism, and which the smallest? Cut two 2-mm. slits in the cardboard, and leave a 2-mm. space between them. Cover one slit and note the spectrum; then uncover and note the change in color in the middle of the patch where the two spectra overlap. Does this show that the spectral colors may be recombined into white light? Hold the prism alone without any slit in the sunlight. Explain now why only the edges of the patch appear colored, while the middle appears uncolored.

(*b*) Now place the prism immediately before the eye in such a way that you can observe through it a narrow (2-mm.) strip of white paper placed on a black background, or better still, an electric-lamp filament, or the narrow edge of a gas flame. Explain why the red now appears to be on the side next the base of the prism, while the blue is nearer the apex. Substitute a broad sheet of paper for the narrow strip. When viewed through the prism, one edge will appear red shading into yellow on the inner

side, and the other will appear blue shading into green. Explain why the paper does not appear colored in the middle, while it does appear colored at the edges. Explain further why the two edges are differently colored.

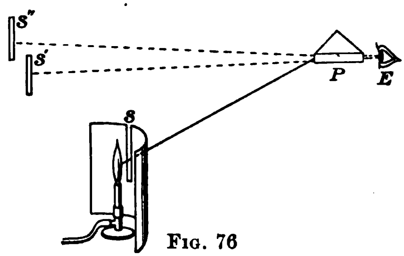


Fig. 76

III. Bright-line spectra. Let one student hold successively in a Bunsen flame arranged as in Fig. 76 platinum wires, or bits of asbestus, which have been dipped, one in a solution of common salt (sodium choride), another in lithium chloride, and another in calcium chloride, taking care that the wire itself is kept below the lower edge of the slit *s*. Let other students observe through the prisms at distances of about 10 ft., in the manner indicated in the figure, and record the character of the spectra which the incandescent vapors of these substances give rise to.

IV. Path of a beam of light through a plate of glass with parallel faces. (*a*) Place two prisms together in the manner shown in Fig. 77, thus forming in effect a single piece of glass with the parallel edges *om* and *pn*. Draw a heavy line *AB*, then place a straightedge in line with the image of this line, and draw a mark *A′B′* along its edge showing the direction of the light after passing through the parallel faces *om* and *pn*. From the result obtained, state what happens to the direction of a ray of light which passes through a plate of glass with parallel faces.

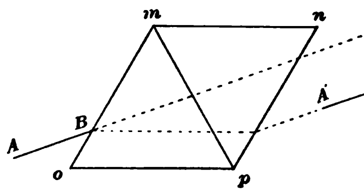


Fig. 77

(*b*) Hold one prism firmly in place and slide the other along the common face until the effective thickness of glass between

the faces *mo* and *pn* is only one half as much as before, i.e. until the vertex of one prism falls at the middle of one side of the other, as shown in Fig. 78. With the same line *AB* and the face *om* exactly parallel to its initial position, draw again a line $A'B'$ in the apparent prolongation of *AB*.

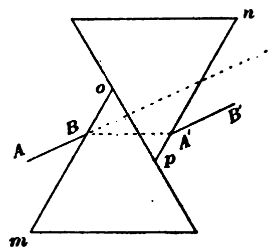


FIG. 78

(*c*) Slide the prisms into the position shown in Fig. 79, being very careful to keep the face *om* parallel to its initial direction. The thickness of glass to be traversed will now be three times as great as in (*b*). Proceed precisely as above.

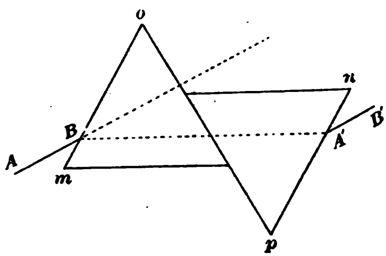


FIG. 79

(*d*) Remove the prisms and prolong *AB*. Measure the perpendicular distances between *AB* and the three prolongations of *AB* as seen through the three thicknesses of glass. State in what way the experiment shows that the lateral displacement of the beam varies with the thickness of the glass.

(*e*) If the prisms are so placed that *AB* is perpendicular to the face *om* (Fig. 80), no trace of the line can be seen at $A'B'$. But if a drop of water is placed between the faces in contact along *mp*, the line *AB* can be seen very plainly at $A'B'$. Explain.

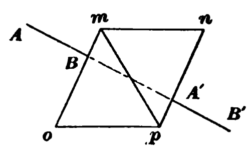


FIG. 80

If now $A'B'$ is drawn as above and if *AB* is exactly perpendicular to *om*, then on removing the prisms and extending *AB* it will be found that *AB* and $A'B'$ lie on the same straight line, i.e. there has been no lateral displacement. Why?

EXPERIMENT 51[1]

PHOTOMETRY

I. Law of inverse squares. Set up a paper screen with an oiled spot in the middle between a single candle on one side and a group of four candles on the other. See that the flames of the five candles are as nearly as possible of equal height; then move the screen back and forth until a position is found in which the paper screen appears equally illuminated from both sides. At this point the oiled spot will either entirely disappear or will at least appear just alike when viewed from either side. Measure the distance from the single candle to the screen and also that from the group of candles to the screen. The intensities of the two sources are evidently in the ratio 1 to 4. What is the ratio of the distances? What is the ratio of the squares of the distances? How, then, does the intensity of the light from a given source vary with the distance from that source?

II. Candle power. Replace the four candles by a gas flame or an electric lamp, and find by the law just discovered to how many candles it is equivalent, i.e. find its candle power.

[1] This is an extra experiment inserted only for the sake of schools which are equipped with a dark room. Since it is impossible to have all of the students working upon it at the same time, even with a dark room, it is a subject which, when classes are large, the authors prefer to treat from the class room rather than from the laboratory standpoint.

APPENDIX A

SUGGESTED TIME SCHEDULE FOR A ONE-YEAR COURSE

Chapter	Subject	Time Allotted	Experiments Accompanying
1	Measurement	1 week	1 and part of 2
2	Force and Motion	$2\frac{1}{2}$ weeks	2 to 5
3	Pressure in Liquids	2 weeks	6 and 7
4	Pressure in Air	2 weeks	8 and 9
5	Molecular Motions	2 weeks	10 to 12
6	Molecular Forces	1 week	13 and 14
7	Thermometry and Expansion	1 week	15
8	Work and Mechanical Energy	2 weeks	16 to 18
9	Work and Heat Energy	2 weeks	19 to 21
10	Change of State	1 week	22 and 23
11	Transference of Heat	$\frac{1}{2}$ week	24
12	Magnetism	$\frac{1}{2}$ week	25
13	Static Electricity	2 weeks	26, 27, and part of 28
14	Electricity in Motion	$2\frac{1}{2}$ weeks	28 to 31
15	Chemical, Magnetic, and Heating Effects of Currents	$1\frac{1}{2}$ weeks	32 and 33
16	Induced Currents	$2\frac{1}{2}$ weeks	34 to 37
17	Nature and Transmission of Sound	2 weeks	38 to 40
18	Properties of Musical Sounds	$1\frac{1}{2}$ weeks	41 and 42
19	Nature and Propagation of Light	2 weeks	43 to 45
20	Image Formation	2 weeks	46 to 48
21	Color Phenomena	$1\frac{1}{2}$ weeks	48 and 49
22	Invisible Radiation	1 week	50
	Total	36 weeks	

APPENDIX B

RESISTANCES OF COPPER AND OF GERMAN SILVER WIRE

Brown and Sharp Gauge

		Pure Copper	18% German Silver
Number	Diameter in Mils ($\frac{1}{1000}$ in.)	Ohms per 1000 ft.	Ohms per 1000 ft.
15	57.07	3.314	59.652
16	50.82	4.179	75.222
17	45.26	5.269	94.842
18	40.30	6.645	119.610
19	35.89	8.617	155.106
20	31.96	10.566	190.188
21	28.46	13.323	239.814
22	25.35	16.799	302.382
23	22.57	21.185	381.330
24	20.10	26.713	480.834
25	17.90	33.684	606.312
26	15.94	42.477	764.586
27	14.20	53.563	964.134
28	12.64	67.542	1215.756
29	11.26	85.170	1533.060
30	10.03	107.391	1933.038
31	8.93	135.402	2437.236
32	7.95	170.765	3073.770
33	7.08	215.312	3875.616
34	6.30	271.583	4888.494
35	5.61	342.443	6163.974
36	5.00	431.712	7770.816
37	4.45	544.287	9797.166
38	3.97	686.511	12357.198
39	3.53	865.046	15570.828
40	3.14	1091.865	19653.570

APPENDIX C

APPARATUS

This list includes all of the pieces which are desirable for the thoroughly satisfactory conduct of the preceding course. The total cost of a single set can be reduced about $20 by omitting a few pieces which, while desirable, are not at all essential. Some of the more expensive pieces do not need duplication even for large classes, so that the average cost of a set is considerably less than the total given below.

1 meter stick, p. 1	$0.25
1 brass disk, p. 1	.25
1 balance with counterpoise, pp. 5, 19	10.00
1 set weights with holder, pp. 5, 19, 35, 36	1.60
1 Brown and Sharp micrometer caliper with ratchet stop, p. 9	5.00
2 brass cylinders with glass cover, pp. 3, 10, 55, 57	.80
8 steel balls 2 cm. diameter, pp. 10, 48, 74	.40
3 spring balances, 2000 g., pp. 11, 13	1.65
1 parallelogram law board, p. 13	1.25
1 glass tube 110 cm. by 4 cm., ends annealed, rubber stopper, pp. 14, 22, 110	1.75
1 manometer bottle with inlet tube, pinchcock and manometers, p. 18	1.50
1 aluminum cylinder, p. 19	.40
1 constant-weight hydrometer tube, p. 22	.40
1 constant-volume hydrometer tube, p. 23	.30
1 wooden block with sinker, pp. 24, 25	.30
1 Boyle's law tube, p. 27	$0.30
1 tripod, rod, clamp, burette holder, pp. 27, 37, 47, 48, 110, 120, 124	1.75
3 bottles 125 cc., pp. 18, 30	.10
3 evaporating dishes 5 cm., p. 30	.25
1 mirror scale and support, pp. 35, 36, 41	1.25
1 thermometer, $-20°$ C. to $110°$ C.	.50
1 spring and weight holder for Hooke's law, p. 35	.35
1 dew-point apparatus, p. 33	1.00
1 steel rod; 2 wooden support blocks, pp. 36, 41, 73, 120, 122	.75
1 pressure-coefficient-of-air apparatus, p. 37	1.75
1 tube for volume coefficient of air, p. 39	.15
1 steam generator, pp. 37, 39, 41, 55, 69	1.90
1 apparatus for expansion coefficient of brass, p. 41	.75
1 demonstration balance (knife-edge and support), p. 44	.65
1 inclined plane and sonometer, pp. 47, 111	1.55
1 carriage for inclined plane, p. 47	.90
1 pendulum clamp, p. 48	.35
1 boiling-point-of-alcohol tube	.30

1 spun-brass calorimeter, two vessels, 300 cc. and 1000 cc., pp. 52, 55, 59, 65, 67, 77	$2.50
1 tube for mechanical equivalent of heat, p. 59	.65
1 high-grade compass, pp. 71, 80, 83, 88, 90, 92, 94, 98, 100	1.35
1 small bottle acetamide, p. 63	.50
1 bar magnet, pp. 70, 103	.40
1 horseshoe magnet, pp. 71, 105	.25
1 electroscope. pp. 74, 77, 78	.50
1 galvanometer frame with three windings, pp. 80, 88, 90, 92, 93, 97, 100	1.60
1 simple voltaic cell (complete), pp. 80, 83, 86, 88, 90, 101	.65
1 porous cup for Daniell cell, pp. 81, 87, 91, 97, 100	.10
1 D'Arsonval galvanometer (complete), pp. 86, 96, 103, 104, 105	2.20
1 1000-ohm resistance coil, pp. 87, 90, 101	.30
1 each of carbon, aluminum, and lead electrodes, p. 89	.15
2 lead electrodes, p. 101	$0.10
1 Wheatstone's bridge with potentiometer attachment, pp. 81, 92, 94	2.20
1 commutator, pp. 83, 86, 104	.75
1 1-ohm resistance coil	.40
2 dry cells, pp. 99, 104, 106	.45
2 coils for induction, pp. 103, 104, 105	1.00
1 electric bell, p. 106	.30
2 electric push buttons, p. 106	.25
1 electric motor, mounted, p. 106	1.25
3 tuning forks (256, 384, 512), pp. 110, 111	3.00
1 fork-rating apparatus, p. 108	3.75
1 glass plate, lacquered black on back, p. 113	.05
2 prisms, pp. 115, 116, 125, 126, 127	2.20
1 concave mirror, p. 118	.45
1 convex, mounted reading lens, pp. 119, 122	.45
2 linen tester lenses, pp, 121, 123	.65
1 microscope tube, p. 124	.20
Total	68.00

INDEX